# Geology for Engineers

*By*


JOSEPH M. TREFETHEN, PH.D.
*Professor, Department of Civil Engineering*
*University of Maine*


*SECOND EDITION*



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# PREFACE TO THE SECOND EDITION

In this second edition changes have been made in the text both by addition and deletion, and by some rearrangement. Fundamentally, as in the previous edition, the book consists of two parts: first, a consideration of the materials of the earth's outer portion, their constituents, arrangements, properties, and representation; next, a consideration of the geologic processes that act on the works of man as well as on natural materials. This primary organization has been helpful to the student as well as useful in teaching. No sequence of chapters in any text is ever satisfactory in all respects to any instructor, even to the author. To us, however, it has seemed logical to start with minerals and follow with igneous activity, weather the products, derive the sediments, follow the deformation and metamorphism of the rocks, and then discuss the field methods and geologic maps that aid these studies. It is helpful in understanding a geologic map and many geologic reports if a little geologic history is a part of the background. The work of surface agents then follows.

In the present edition some of the fundamentals of soils mechanics are introduced in Chapter VI, which is substantially new. This offers a background for student engineers, whose subsequent training should include more than a superficial acquaintance with that field if they are to qualify as foundation engineers. There is no short cut to engineering competence. We have found that the geologic principles of rock and soil behavior presented here have served the student engineer well in subsequent studies and practice.

J.M.T.

# PREFACE TO THE FIRST EDITION

The purpose of this book is to present certain fundamentals of geology to the engineering student, who will very likely be confronted with various geologic problems early in his professional apprenticeship. It is hoped that this presentation will enable the engineer himself to employ his knowledge of geology as a tool, as well as to use the geological investigations of others.

The engineering student who approaches geology for the first time, fresh from courses in physics, mechanics, and surveying where data are quantitative and results are precise, is often surprised and repelled by the necessarily meagre quantitative data and qualitative approach. This is an altogether healthy and natural attitude. Although some phases of geology have been rigorously treated for years, in many phases the science is only now at the beginning of the quantitative stage. Nature has imparted limits that can be appreciated best in the field. Geological structures were not designed by handbook and slide rule; heterogeneity of material and slope, of composition, structure, and water content, of strength, hardness, and solubility, and of many other elements prevails—heterogeneity that precludes mathematical analysis or rigorously quantitative treatment of some phases.

Many engineering projects require the services of one or several professional geologists who are specialists in the particular part of geology in question. These men are consultants who assume no responsibility for the final success or failure of a project; that responsibility rests on the engineer in charge. The consultant's job is to present geological data bearing on a particular problem or series of problems clearly, fully, specifically, and quantitatively within the

limits set by the employer and those set by nature. The engineer wants numbers representing answers to certain definite questions. A false sense of security and mastery of matter is sometimes the result of assumptions of numerical data or from extension of numerical data to unwarranted applications. An assumption may be concealed by mathematical transformations or obscured by constant repetition. However, the engineer must have, find, or assume satisfactory quantitative answers for many problems. And in the process of arriving at them he has made valuable contributions to geological knowledge. The science of geology, nevertheless, even where qualitative, may serve the engineer well and, while receiving much from engineering practice, gives much to the practicing engineer.

J.M.T.

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# ACKNOWLEDGMENTS

The author is indebted to many, both students and professional colleagues, for much contained in this volume. During ten years of teaching geology to civil engineering students, assimilation of the ideas of others, as expressed in the literature, precludes giving singular credit to individuals responsible at some places in the text where credit is undoubtedly due. The extent to which the influence of Mead, Leith, Winchell, and Twenhofel is reflected in this book will be apparent to all familiar with their works and teaching, and to them grateful acknowledgment is made. Thanks are also made to those who have generously furnished illustrations. These are individually credited. Most of the drafting has been done by Robert M. Chase; several of the maps were drawn by Weston S. Evans Jr. Prof. Weston Evans, Dean of the College of Engineering, University of Maine, has assisted in the preparation of the manuscript. The most significant acknowledgment, however, is to my wife, Helen B. Trefethen, who has patiently assisted throughout the preparation of the text.

## CHAPTER I

# GEOLOGY AND ENGINEERING

EVER SINCE MAN IN THE DIM AGES OF PREHISTORIC TIME first practiced the arts of engineering, he has been confronted with problems of material and process. By the time human progress had reached that evolutionary height called "civilization", man had begun to build structures; he had become in fact and in deed an engineer. Experience taught him much, and empirical engineering was far in advance of theoretical science for generations. However, in modern times the civil engineer relies less upon rule of thumb and draws increasingly from the various sciences. Whereas there are those, whose minds turn ever backward in time, to whom the arts, crafts, and engineering skills of ancient peoples constitute unsurpassed wonders, the realist recognizes that today's feats of engineering are as far in advance of those magnificent structures of antiquity as the "mechanical brain" is in advance of the abacus, not to detract in the least from the latter admirable instrument nor from those early structures.

In modern engineering, safety factors have been reduced; innovations of all kinds—of materials, of methods, of function—have been introduced; and the scales of size, weight, and use have been multiplied many fold according with the advances of technology. No structure, however, is better than its foundation or than the material it is made of; indeed, the majority of modern failures are those due in some measure to underlying geological causes. With recognition of these causes of failure, and because of the responsibility inherent in large-scale construction, which by the building of a single large dam, for example, may entail hundreds of lives and hundreds of

thousands of dollars worth of property, the use of geology as a tool or engineering has become an integral part of modern engineering practice.

In a competitive economy good engineering is not creating the best possible structure; good engineering is making the most economical structure that will satisfactorily fulfill its purpose. In the interests of economy, therefore, as well as safety, more and more use is made of geological skills: in the investigation of sites; in the search for construction materials; during construction; and in some types of engineering, continuing through operation and maintenance. Illustrations of economy in construction made by virtue of geological examinations are commonplace today. A few examples will illustrate the point. The decision to leave unlined a 19-mile stretch of the Friant-Kern Canal, based on knowledge of the underlying rock, saved an estimated $2,000,000.[1] At Kortes Dam, Wyoming, it was considered that no local sand and gravel suitable for concrete was to be found. A geological examination revealed a suitable source close by.[2] On a county road job in Maine several years ago a crew of forty men, four trucks, and a shovel operator were kept idle for half a day while the engineer in charge tore wildly around with a test-pit crew trying to locate a new gravel bank—the shovel had been set into a bedrock ridge; the new spot selected for operation proved to be the same. In one state, a soils specialist conducted a material survey for a 20-mile stretch of concrete highway. His boast was that every slope within 10 miles of the job was test-pitted. He overlooked some "flats" of glacial outwash. Evidently even on small jobs economies are possible if geology can be applied at the right time and place.

## Use of Geological Training for the Engineer

The civil engineer meets a variety of problems in which geological training is of service. Inevitably he will learn more geology in

[1] Rhoades, R., and Irwin, W. H., "What the Engineering Geologist Does," *Eng. News Record,* Vol. 139, 1947, p. 528.
[2] *Ibid.*

the field and in practice than can be taught in classroom or college laboratory. But he will learn it more quickly and apply it more effectively if his engineering course has included the basic principles of geology. Several specific advantages of this training are singled out for particular mention.

First: it gives him a systematic knowledge of *materials,* their occurrence and properties. Although every contractor or engineer who deals with rock or soil gains this knowledge the hard way by experience, the path is smoother and straighter for the young engineer who has studied them under professional guidance. The sources, types, and characteristics of geological materials therefore are geological fundamentals for engineers.

Second: *foundation problems* are directly geological. Buildings, bridges, dams, highways, and other structures are built on or in some natural material.

Third: *excavation,* whether open or underground, can be more intelligently planned, directed, and more safely carried out if cognizance is taken of the type and structure of the material to be removed.

Fourth: a knowledge of *groundwater* occurrence and the elements of groundwater hydrology is helpful in many branches of engineering practice: in sanitary engineering, water supply, land drainage, irrigation, excavation, control of landslide, and many other works.

Fifth: a knowledge of *surface waters,* their methods of erosion, transportation, and deposition, is essential for river control, coastal and harbor works, soil conservation, and other projects.

Sixth: the ability to *read and interpret geologic reports, geologic and topographic maps, and photographs* is of assistance in planning most projects. The nature and distribution of soil and bedrock types and structures can often be deduced successfully from the topographic map or aerial photograph. A good geologic map can be translated into a three-dimensional picture or model of the area. Ability to interpret geologic maps is essential, also, to the comprehension of geologic reports.

Seventh: an ability to *recognize the nature of geologic problems*

as they are encountered and to single out those which require a specialist's study is a valuable asset; and a familiarity with the concepts of geology and with the technical language that often obscures them is likewise often of value.

Not all of these advantages will be realized from any program of formal study. Many experienced contractors and engineers seem almost intuitively to recognize and solve the simpler geologic problems. Others of equal experience and added study never seem to assimilate or apply simple geological principles. For the majority, however, who fall into intermediate classes, geology will be a useful tool.

### References

The following references for this chapter and those at the ends of succeeding chapters are selected both for content and general availability. The textbooks cited are standard, and the few periodical articles listed are of outstanding interest and value to engineer and geologist alike. The books and articles recommended contain many references to source material. For other sources of geologic information see Appendix I.

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# CHAPTER II

# MINERALS

MANY PROBLEMS OF ENGINEERING PRACTICE RELATE TO rocks or soil. Inasmuch as both are largely or wholly composed of minerals, some familiarity with the common minerals is a prerequisite to the successful study of earth materials.

### ROCKS AND MINERALS

In the field, a variety of materials are observed, some of which are classed as rocks and some of which are classed as minerals. Although these two are sometimes confused, they are easily differentiated. To the geologist, the sand found at the bottom of a stream or along the shore of sea or lake is rock. In ordinary conversation, however, the term *rock* is generally restricted to those substances which are firm and coherent. If a handful of beach sand is carefully examined, it will be noted that it is composed of a variety of individual grains, many of which may be white, but some of which may be black, red, or other color. If a careful count were made of the different individual types of grains represented, a formula for the handful of material could be written. Another handful from a different locality, on careful analysis, might show quite different proportions of the several kinds of sand grains. In spite of the differences, because of similarity of origin and mechanical make-up, the cemented equivalents of such sands, even though they differ considerably in the proportions of the black, white, and colored grains, are called sandstone. Careful examination of various rocks picked up at different places shows that they, like the sands, are composed of different mineral constituents. The proportions, manner of asso-

ciation, way in which the different constituents were brought together, and the resulting texture serve as bases for the classification of rocks. It can be seen from the above that no satisfactory chemical formula could be written for rock types, as rocks going under the same name show rather wide variations. If, however, from a handful of sand, one particular mineral grain were isolated and analyzed, it would be found essentially the same as any other similarly identified grain from anywhere else in the world.

The difference between rocks and minerals might be expressed in another way. Buildings are made of wood, nails, bricks, mortar, steel, and other materials of construction. The proportions of the types of material going into the building, the manner of combining them, the style of architecture, and similar factors give rise to different types of buildings. The bricks of a factory and of a residence, however, are similar; oak may floor a palace or a garage. It is possible to build a house entirely of wood. In the analogy, the building is comparable to a rock; the individual constituents comparable to minerals. Most rocks are made up of several varieties of minerals, but some are composed, as was the completely wooden house, of only one kind of material or mineral.

## The Nature of Minerals

Through the tools of physics and chemistry much has been learned about the nature of minerals. Most minerals are crystalline; that is, they are systematic arrangements of atoms or ions. The packing and bonding of these units determine the characters of the resulting mineral.

The atom, as generally pictured to-day, consists of a positively charged nucleus, which is one or more positively charged protons together with one or more electrically neutral neutrons, surrounded by negatively charged particles of approximately the same size as the

nucleus, the *electrons.* The nucleus contains nearly all the mass of the atom but occupies less than one million-millionth ($10^{-12}$) of the volume of the atom. The electrons are distributed in "shells" about the nucleus, in a maximum of seven energy-level shells.

Ions are atoms that have gained an electron, *anions;* or atoms that have lost an electron, *cations.* Considered as spheres, different kinds of ions and atoms have radii of different lengths. For example, a sodium ion has an ionic radius of .98 Å (angstrom unit = $10^{-8}$ cm); a potassium ion has an ionic radius of 1.33 Å, and a calcium ion, 1.06Å. Thus calcium (with two electrons in the outer shell) can replace or proxy for sodium (with one electron in the outer shell) in all proportions in the crystal structure of plagioclase feldspar, if the electrical balance is maintained by concomitant substitutions of aluminum (three electrons in the outer shell) for silicon (with four electrons). But potassium, with its much larger ionic radius, can enter into the structure of plagioclase to only a limited extent.

In fact very few minerals contain only certain elements in definite fixed proportions. Most minerals contain "foreign" atoms or ions that are able to fit into the structure. And most minerals belong to a series in which one or more elements are proxied for or replaced by certain other elements, to a varying extent which maintains the structure and electrical balance of the crystal.

As is proved by research with X-rays, crystalline materials are orderly arrangements of atoms or ions. The structure of a cubic mineral, *halite* (rock salt, NaCl), is shown diagrammatically in Fig. 2-1. This is an ionic crystal in which electrostatic attraction between the anions and cations holds the ions in relative position. The cubic symmetry of the ionic arrangement also gives a direction of easy splitting (mineral cleavage) parallel to the cube faces of this mineral. Many ionic crystals are known.

Perhaps more abundant than ionic crystals are minerals whose atoms are bonded by the sharing of an electron pair between nuclei, the covalent bond. The common mineral quartz, for example, is made up of a silicon atom surrounded by four oxygen atoms, with each oxygen atom shared between two silicon atoms; the tetrahedral

groups are linked by having common corners Since a silicon atom has a half share of each of the four surrounding oxygen atoms, the

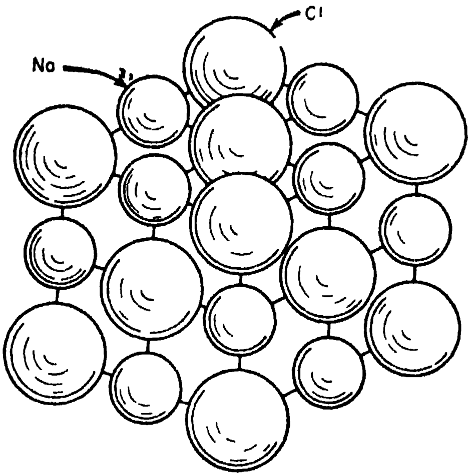
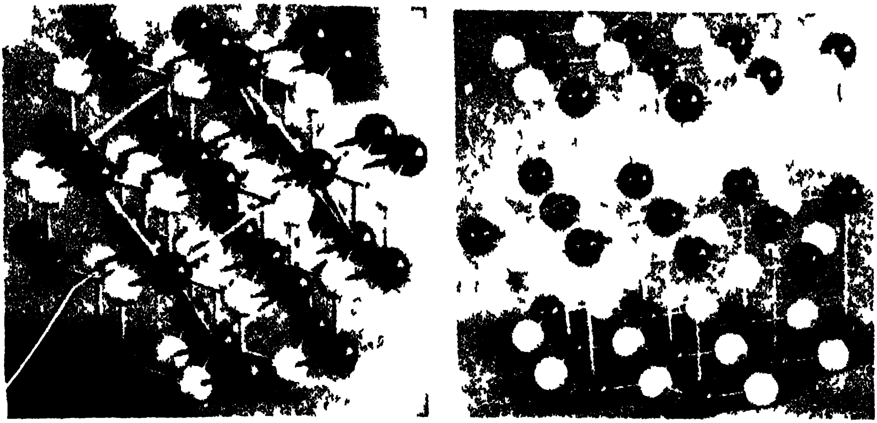



Fig 2 1 The structure of halite—an example of ionic crystals

ratio, $SiO_2$, gives the composition of quartz Another example of a mineral with covalent bonds is the diamond, consisting of carbon atoms Each carbon atom, with four electrons missing from a completed octet, forms covalent bonds with each of four neighboring atoms, thus each carbon atom occupies the center of gravity of a tetrahedron of four carbon atoms at the corners With this arrangement it is easy to see why diamond is so hard If diamond is pressed against another arrangement of atoms less securely bonded, the other arrangement must yield. The model (Fig 2-2a) may be viewed also as made up of layers of atoms parallel to the base, or as parallel to any of the other three sides. Inasmuch as cleavage (smooth parting) in a mineral occurs parallel with planes in which the atoms are closely packed together and normal to which the distance between atomic layers is relatively great (see Fig 2-2a), hardness and other physical properties of the crystal depend on its internal structure and bonding of the atoms or ions. The contrasting properties of diamond



(a) (b)

FIG. 2.2 The structure of diamond (a) and structure of graphite (b). Both are composed of carbon atoms.

and graphite, both made of the one element carbon, result from the different arrangements of the carbon atoms as shown in Fig. 2.2.

### MINERAL IDENTIFICATION

By definition, *rocks are aggregates composed of one or, more commonly, several varieties of minerals.* There are a few exceptions to this rule: not all rocks are composed of minerals—for example, coal.

*Minerals,* however, *are naturally occurring inorganic substances of more or less definite chemical composition, displaying more or less definite physical properties.* They can be readily identified by their physical or chemical properties, the variations in these properties falling within rather narrow limits. Of these two sets of properties, the more easily determined in the field or office are the physical properties. Identification of the minerals by means of the tables of Appendix III depends upon the determination of:

1. *Color* and *streak*
2. *Cleavage* and *fracture*
3. *Hardness*

4. *Luster*
5. *Structure*

Other physical characteristics of lesser importance in the identification of most minerals are crystal form, specific gravity, and magnetism. In addition, associations of other minerals and type of occurrence are often helpful.

***Color.*** The color of a mineral, as shown in the bulk material, is often of assistance in its identification. There are two types of color shown by minerals. The first of these, inherent color, due to the composition of the mineral and the arrangement of the constituent atoms, is characteristic of the mineral and can be used with more or less success in limiting the possibilities in identification. The common mineral pyrite (fool's gold) is brassy yellow; galena (lead sulfide) is steely gray. These colors are inherent and always are shown by the fresh material. The second type of color is exotic, in that it depends on the presence of impurities or on fracturing in the material. Quartz, for example, is inherently colorless, but it is sometimes rosy, smoky, or milky. Calcite is inherently colorless. It is commonly whitish or yellowish, but often buff and sometimes pinkish or bluish. Many other examples could be given. In using color for purposes of identification, then, some reservations must be made. The property of color in conjunction with other properties is useful, however, and variations due to exotic pigmentation are in general indicated in tables for the identification of minerals.

***Streak.*** More characteristic than color and hence of more use in mineral identification is the color of the mineral in powdered form. This powder is readily obtained by crushing the mineral to a fine powder or by marking on some hard, slightly roughened surface. It is generally convenient to have a white surface to mark on; the unglazed portion on the back of a tile, a piece of chert, or, less satisfactorily, a piece of feldspar will serve. Such materials used for determining the streak are called "streak plates." The streak of chalk, for example, is white; and the marks left by chalk on a blackboard are the streaks of chalk. Hematite is another good example.

This mineral, the common ferric oxide, may be red, black, or steely gray; the streak is always a reddish-brown. In taking the streak of micaceous minerals, scales may come off too large in size to give the characteristic color of the mineral in powder. Thus, in taking the streak of biotite, scales of the mica may give the impression that the streak is much darker than it actually is. In taking the streak of an oxidized or rusty specimen, care should be taken to get the streak of the fresh mineral, not the streak of a coating of limonite, hematite, or other altered portion.

If the mineral is harder than the streak plate, it will be necessary to powder the mineral other than by means of a streak plate. The great majority of the harder minerals have pale streaks. For example, although the color of tourmaline is rarely white, being sometimes pink or green and often black, the powder is always light or colorless.

***Cleavage.*** The cleavage of the mineral is its capacity to split more readily in certain directions than in others, due to the arrangement of the atoms. Some minerals such as the common micas have perfect cleavage in one direction. Mica can be scaled into remarkably thin elastic sheets parallel to the direction of cleavage; in all other directions the mineral breaks very irregularly. A consideration of the crystal structure of mica explains this property. The micas are made up of sheets of $SiO_4$ tetrahedrons. These Si-O bonds are among the strongest in minerals. Three of the four oxygen ions are shared with neighboring tetrahedrons. The tetrahedrons lie alternately base to base and vertex to vertex and are held together by the relatively weaker oxygen-cation bond. The Si-O bonds are in the plane of the sheet; hence the relatively slight hardness and flexibility of the cleavage flakes, and the perfection of the cleavage.

Other minerals have the property of cleaving in two directions. The feldspars, which are the most abundant of all minerals, have two cleavages nearly or exactly at right angles to each other. Other minerals have more than two directions of easy parting. Ordinary salt, for example, has three cleavages at right angles to one another. This can be verified by taking a pinch of salt from a salt shaker and examining it under a magnifying glass.

Not only the number of cleavages but also the perfection of cleavages should be noted. For example, the feldspars show smooth shiny surfaces from the breaks along cleavage planes; but one of the directions of cleavage is a little easier than the other, although neither is nearly as perfect as the cleavage of mica. In minerals which show more than one cleavage, the angular relation of the cleavage planes should be noted. As has been mentioned, the mineral feldspar shows two cleavages nearly or exactly at right angles to each other. Hornblende, a common mineral generally black or some shade of green, has two cleavages making angles of 56° and 124°. Augite closely resembles hornblende in color, streak, and hardness, but has two cleavages nearly at right angles to each other as shown in Fig. 2-3.

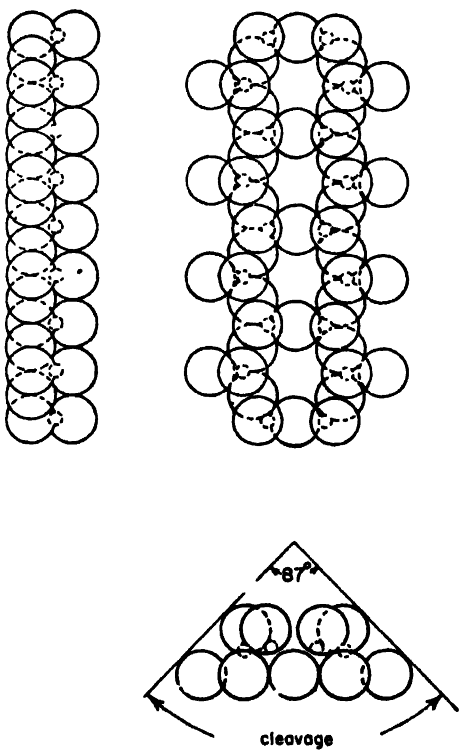



**Fig. 2-3.** The structure of pyroxene (augite). (After Leet and Judson)

Some minerals show no cleavage directions at all. Quartz is the most common example of this class. Other minerals may have good cleavage or fair cleavage; but its presence may be difficult to detect without the aid of the microscope because of the mode of occurrence of the material, as for example in granular aggregates. The common mineral olivine is an example of cleavage difficult to detect in hand specimens because of the granular character of the material. Small grains aggregated into a rock may show shiny cleavage faces, but the number and angular relations of the cleavages may be impossible to determine without the aid of higher magnifications than are ordinarily available.

Cleavage is best determined by holding the specimen up to the light and slightly rotating it in various directions so as to catch the light on the cleavage surfaces, which reflect brilliantly like little mirrors. It should be remembered that cleavage is a direction and that cleavability depends upon the presence of closely spaced parallel planes of easy parting; hence, if one cleavage plane is discovered, others in parallel position should also be discovered. Mica, for example, has innumerable parallel planes of easy parting, but it is said to have only one perfect cleavage. By catching the light on the cleavage plane of a mineral showing more than one cleavage, and rotating the specimen until another cleavage plane catches the light, the angular relation between the two cleavages may be estimated.

Some minerals have a mechanically induced parting, not due to atomic arrangement, which may be mistaken for cleavage. Generally, these surfaces of parting are not as smooth as cleavage surfaces, and commonly they are not as closely spaced as cleavages. Beginners frequently have difficulty in picking out cleavage or recognizing its presence. The ability to recognize cleavage grows with practice.

***Fracture.*** The fracture of a mineral is the way the mineral breaks. In some instances, this characteristic may be useful, although the majority of minerals break irregularly in directions other than cleavage or parting. One special type of fracture—the conchoidal, or shell-like, fracture—leaves the specimen with smooth, somewhat rounded surfaces marked with concentric rings, giving a resemblance

to a clam or oyster shell; hence the expression *conchoidal* fracture. Another type gives splinters of the mineral material; hence the expression *splintery* fracture. Quartz shows conchoidal fracture under some conditions, and hornblende tends to have a splintery fracture.

***Hardness.*** The hardness of a mineral, as commonly determined on fresh material, is measured by its ability to resist scratching. If a mineral is scratched by a knife, it is softer than the knife. If it cannot be scratched by the knife, the two are of equal hardness or the mineral is the harder. If the knife is scratched by the mineral, the mineral is the harder. In order to have a standard method of expressing hardness of minerals, a simple scale, known as the *Mohs scale,* has been universally adopted. In sequence of increasing hardness from 1 to 10, the following minerals are used as standards of comparison:

| | |
|---|---|
| 1. Talc | 6. Orthoclase (Feldspar) |
| 2. Gypsum | 7. Quartz |
| 3. Calcite | 8. Topaz |
| 4. Fluorite | 9. Corundum |
| 5. Apatite | 10. Diamond |

Calcíte, quartz, or feldspar (orthoclase) can usually be picked up in the field, in gravel pits or from ledges. However, there is always available a knife, coin, piece of glass, or key to use as a measure of relative hardness; and it is a simple matter to determine the hardness of one of these objects and use it as a hardness scale. A copper coin, for example, has a hardness of about 3. Window glass has a hardness of about 5. It is used as a standard in the accompanying identification tables because it is easy to determine whether or not a mineral specimen will scratch a smooth glass surface. A knife blade, depending on the quality of the steel, has a hardness of between 5 and 6½.

With a little experience, the approximate hardness of a mineral can be estimated with the knife blade alone. The ease or difficulty with which the mineral is scratched measures the degree of hardness. The half-marks between the numbers of the hardness scale are esti-

mated. The thumbnail, for example, readily scratches gypsum, and generally fails to scratch calcite; hence is estimated at 2½. Some individuals have harder nails and can scratch calcite. The scale of hardness is not a mathematical progression. Gypsum is not exactly twice as hard as talc, for example; nor is fluorite exactly twice as hard as gypsum. It is said that diamond, hardest of substances and 10 in the Mohs scale, is as much harder than corundum as corundum is harder than talc. It should be remembered that fresh material must be used to determine hardness.

***Luster.*** Luster is the appearance of the mineral in ordinary light (the appearance due to the light reflected from its surface). If the mineral looks like metal as do galena and pyrite, its luster is said to be *metallic.* If the mineral looks glassy, like quartz, its luster is *vitreous* or *glassy.* Other minerals are *dull* or *earthy* in appearance, as kaolin; *silky* in appearance, as satinspar (a form of gypsum); or *greasy* looking, as nepheline. *Pearly* sheen or luster is shown by some minerals, as for example some forms of talc. All minerals with metallic luster show a dark streak.

***Structure.*** Some minerals are granular, as, for example, olivine; others are bladed, as kyanite; or fibrous, as chrysotile. Some are botryoidal, as, for example, some forms of hematite, which occur as rounded masses and in appearance are somewhat like bunches of grapes grown together. Many occur as crystalline masses whose structure is not apparent. The terms are descriptive.

***Other Characteristics.*** Although the preceding physical properties generally suffice to identify a mineral, it is frequently useful and sometimes necessary to determine additional characteristics. Crystal form, specific gravity, degree of magnetism, and association with other minerals are auxiliary and sometimes diagnostic aids to correct identification.

*Crystal Form.* Internal atomic arrangement in definite geometric patterns is sometimes outwardly expressed in crystal form. The various forms can be referred to six crystal systems, according to the position of the axes which are imagined as the skeleton on which the crystal is built. Quartz, for example, commonly occurs as a six-sided

prism, generally terminated by a six-sided pyramid. Pyrite occurs commonly as cubic crystals, often with striated surfaces. Garnet commonly occurs in dodecahedrons. In rocks, owing to the fact that several minerals have generally crystallized at the same time and contended with each other for space, crystal form is rarely discernible in the minerals. The quartz of a granite, for example, does not take on the characteristic crystal outline of that mineral but appears as irregular grains. However, this lack of external crystal form does not imply that internal crystalline arrangement of the constituent atoms is lacking; it simply means that during crystallization, conditions were unfavorable to the growth of regular crystals.

*Specific Gravity.* By specific gravity is meant the weight of a substance compared with the weight of an equal volume of water. Thus a cubic inch of quartz weighs 2.65 times as much as a cubic inch of water. The specific gravity of quartz is 2.65. Some minerals are relatively light, some are very heavy. Thus barite, the sulfate of barium, is heavy, and this weight is sufficiently noticeable to give a clue to its identity. Other minerals, such as galena, are also heavy and suggest immediately certain possibilities, eliminating others. Because the great majority of minerals, however, fall within the range of 2.55 to 3.2, specific gravity, unless determined accurately in the laboratory, is of little assistance in identifying hand specimens.

*Magnetism.* A few minerals are attracted by a magnet. Of these minerals, magnetite and pyrrhotite are the most common examples. Some geologists magnetize a knife blade and thus have a weak magnet with them in the field.

*Association.* The association of certain mineral species is suggestive. For example, a rather peculiar igneous rock known as *litchfieldite,* a variety of syenite, has blue sodalite, yellow cancrinite, nepheline, and zircon in addition to the more abundant feldspar and a black mica. The presence of the easily recognized sodalite and yellow cancrinite suggests the presence of nepheline and the absence of quartz. The fact that sodalite, cancrinite, and nepheline are low-silica minerals indicates that there was not enough silica in the magma (melted rock solution) to form quartz. Olivine is

another mineral that does not occur commonly with quartz; and although quartz veins may occur through the rock, they are of more recent origin. Another example of mineral incompatibility is muscovite and augite.

*Summary.* The determination of the physical properties of minerals by simple tests readily performed in the field, without laboratory equipment, suffices in many if not most instances to identify a mineral. Generally, it is not necessary to determine all the physical properties. Cleavage, hardness, streak, and occurrence often suffice. The combination of physical properties warrants naming the mineral. For example, quartz and feldspar, both occurring in the same rock, can be readily distinguished upon the recognition of the cleavage faces of the feldspar. Feldspar and calcite may be readily separated on the basis of the hardness, and most minerals can be determined by the combination of physical properties exhibited.

## The Rock-making Minerals

One hundred and three elements have been recognized by chemists. Of this number, however, there are only eight that enter into the composition of the earth's outer portions in abundance; in fact, these eight elements make up some 98 per cent of the observable portions of the earth. These are in order of abundance: oxygen (O), silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), sodium (Na), potassium (K), and magnesium (Mg). Of all the possible combinations of these eight common elements that might occur in nature, only a few, in the form of the commonest minerals, make up the great bulk of the rocks. These few are feldspars (silicates of K, Na, and Ca, with Al), quartz (Si and O), the micas (complex silicates of K, Fe, Mg, Al, with a little water, and sometimes other elements in substitution for those mentioned), amphiboles (complex hydrous silicates of Ca, Fe, Na, Al, and Mg), the pyroxenes (very similar chemically to the amphiboles but lacking the water), and olivine (Mg, Fe, Si, and O). Others very common, but composing a lesser portion of the earth's outer crust, are calcite (Ca, C, and O), and

kaolinite (Al, Si, O, and water). Calcite composes the bulk of the limestones; kaolinite predominates in the clays. In addition, the iron oxides, hematite and limonite are very widely distributed as coloring agents in rocks.

A relatively few minerals constitute by far the bulk of the common rocks, and sight recognition of these few is essential to rock classification. The following mineral descriptions include only the most commonly occurring minerals.

***The Feldspars.*** The feldspars are the most abundant minerals. The group is of particular interest and importance because the kind and abundance of feldspar serve as the basis for detailed classification of the igneous rocks. Although correct determination of the varieties of feldspar requires careful laboratory investigation beyond the scope of elementary routine, a visual estimate of the relative quantity of feldspar in medium and coarse textured rocks is easily made, as is an approximate identification of feldspar type that suffices for field naming of rocks.

The feldspar family consists of two major divisions, the potash feldspars and the soda-lime feldspars. Potassium feldspar, *orthoclase* or *microcline* has the formula, $KAlSi_3O_8$. The soda-lime feldspars, *plagioclase,* constitute an isomorphous series (solid solution series) in which the composition varies continuously from $NaAlSi_3O_8$ at one end of the series to $CaAl_2Si_2O_8$ at the other end.

All of the feldspars have the same general physical properties. Inherently they are white, but shades of pink and gray are common. In rocks that have both red and white or gray feldspar, the red or pink is commonly orthoclase, the gray or white plagioclase. The streak is light or colorless, and the hardness is 6. Potassium feldspar and plagioclase have two good cleavages; the cleavage directions of orthoclase are at right angles to each other, and those of plagioclase approximate a right angle. The luster of both varieties is vitreous to pearly. The feldspars often occur as tabular or lath-shaped crystals.

Potassium feldspar is most at home in the acid, or light-colored, igneous rocks, associated with quartz and the micas. Plagioclase is particularly at home in the basic, or dark-colored, igneous rocks,

associated with hornblende, augite, or olivine. Both types of feldspar are found in metamorphic rocks, and potassium feldspar in some sediments. Plagioclase is not abundant in most sediments.

Distinction between potash feldspar and plagioclase can often be made by close observation of cleavage surfaces. Plagioclase cleavages often show fine, straight and parallel grooving or striations, called *multiple twinning* striae. In the study of rocks without magnification, however, the association of other minerals is probably the best means of identification. Precise microscopic identification establishes the variety of feldspar present in a rock. If plagioclase is present, its position in the isomorphous series is closely determined, and the proportions of minerals composing the rock are estimated. These laboratory observations of the feldspars are necessary for precise rock classification. For ordinary purposes, however, a satisfactory field classification can be made without recourse to the techniques of the laboratory.

***Quartz.*** Quartz is a very common mineral of simple composition, $SiO_2$. It is usually colorless, white or gray, although varieties occur that are rather dark (smoky), pink (rose), purple (amethyst), green, or yellow. Powdered quartz is always light-colored. The luster is vitreous. Its hardness is 7, and it has no cleavage.

Quartz is abundant in many light-colored igneous rocks and in various sediments and metamorphics. It is also a common vein mineral, filling cracks in rocks through which silica-bearing waters have circulated. Where quartz has crystallized in rock openings, it is often found as hexagonal prisms. In most rocks, however, it is seen as irregularly shaped or rounded grains. The most common associates of quartz are the potash and soda-rich feldspars and the micas. Quartz is readily distinguished from feldspar by its lack of cleavage and its more glassy transparent look. The feldspars are more opaque, with deader white or gray colors, and often with rectangular outlines. Quartz and feldspar are the two most common hard, white or gray minerals.

***The Micas.*** The micas are very abundant minerals which give little trouble in identification. White or colorless mica is the "isin-

glass" familiar to most people through its use in electric toasters, stove doors, and other equipment. There are two common varieties. *Muscovite,* $KAl_2(Si_3Al)O_{10}(OH)_2$, is a potassium aluminium silicate of colorless or silvery tint, pearly luster, and, especially, one very perfect cleavage which permits the mineral to be split into thin elastic sheets that when bent spring back to shape. *Biotite,* the other common variety, is a complex silicate of potassium, magnesium, iron, and aluminum, $K_2(Mg,Fe)_6(SiAl)_8O_{20}(OH)_4$. Biotite is black, brown, or dark green.

Biotite and muscovite are similar in physical properties. Both are soft, 2.5-3, with one perfect cleavage. They are easily scaled from a rock with the knife point. Muscovite is found in light-colored igneous rocks, in metamorphics, and often in sandstones. Biotite is common in light-colored igneous rocks, and in metamorphics, but is rare in sediments.

*The Amphiboles.* Another series or family of minerals, the amphiboles, are common constituents of many rocks. One member of the group, hornblende, is especially common. Hornblende is a complex silicate of sodium, calcium, magnesium, iron, and aluminum, with a small percentage of hydroxyl ions. It is green to black in color, with a vitreous to silky luster and a pale streak. Its hardness is 5-6. Hornblende has two good cleavages which intersect at an angle of 124°. In many rocks hornblende occurs as elongated prisms.

Hornblende is common in acid, light-colored igneous rocks in association with potassium feldspar, both with and without quartz. It is especially abundant in the intermediate igneous rocks (diorites) associated with plagioclase feldspar. It is present also in many metamorphic rocks, but it is rare in sediments.

*The Pyroxenes.* Another family of minerals, the pyroxenes, resembles the amphiboles. A very abundant member of this family is augite. Augite is a complex silicate of calcium, magnesium, iron, and aluminum. Its color is dark green to black, its luster vitreous to silky, and its hardness 5-6. Augite has two cleavages that intersect at nearly right angles. One of the cleavages is often distinctly better

than the other. Augite is commonly associated with plagioclase feldspars in the basic, dark-colored igneous rocks; it is not common in metamorphic or sedimentary rocks.

Augite and hornblende closely resemble each other. Because they are commonly associated with different members of the plagioclase feldspar series, the distinction between augite and hornblende is frequently of assistance in the classification of igneous rocks. The two cleavages of hornblende intersect at an obtuse (or acute) angle; those of augite intersect at approximately a right angle. Hornblende is often found as elongated prisms; augite as shorter, stumpier grains. The two cleavages of hornblende are about equally good, whereas one of the augite cleavages is often distinctly better than the other. Hornblende is more commonly associated with quartz and with primary biotite mica than is augite. And finally, the shade tone of augite-bearing igneous rocks is often darker than the hornblende-bearing rocks. Because these differences commonly suffice to distinguish between the two minerals, and by implication between the members of the plagioclase feldspar series associated with each, the recognition of hornblende and augite is used in the field classification of the igneous rocks (Table 4.1, page 43).

***Olivine.*** Olivine is a green, glassy, and usually granular mineral composed of magnesium, iron, and silica, $(MgFe)_2SiO_4$. Its hardness is 6.5-7, its streak pale, and its cleavage indistinct. Olivine is an essential mineral of some basic rocks and in some is the dominant mineral. Olivine does not occur in quartz-bearing igneous rocks; it is rare in metamorphic rocks and is not found in the sediments.

***Calcite and Dolomite.*** Calcite is calcium carbonate, $CaCO_3$, and dolomite is the calcium magnesium carbonate, $CaMg(CO_3)_2$. Both are commonly colorless, white, buff, or gray, although other tints are found. The streak of each is colorless and the luster vitreous. Both calcite and dolomite have three good cleavages which intersect at angles of approximately 74°; both tend to break therefore into rhombohedrons. The hardness of calcite is 3; that of dolomite 3.5-4. In cold dilute hydrochloric acid, calcite effervesces freely;

dolomite requires powdering or warm acid. Calcite and dolomite are the chief constituents of the sedimentary rocks limestone and dolostone, respectively, and of their metamorphosed equivalents, the marbles. Calcite also is the mineral cement of many granular sedimentary rocks. In addition, it forms veins where subsurface waters carrying calcium bicarbonate in solution have left it; it forms some cave deposits; and it is deposited about some springs.

***Kaolinite.*** Kaolinite is one of many clay minerals. It is probably the most abundantly occurring of that mineral group. Kaolinite is a hydrous aluminum silicate, $Al_2Si_2O_5(OH)_4$. It occurs as aggregates of tiny particles, which in the aggregate have an earthy luster. The odor of kaolinite is rather distinctly "earthy" and a fresh surface sticks to the tip of the tongue. Masses of kaolinite become plastic when wet. The hardness is 1-2.5; the color, when pure, is white, although often tinted gray, bluish, black, or reddish.

Kaolin is the principal alteration product of feldspar under surface conditions and is produced by the weathering of many other minerals. Notable deposits of kaolinite are found as residual products of weathered feldspathic rocks.

***The Iron Oxides.*** The most common iron oxides are hematite, $Fe_2O_3$; hydrous iron oxides that are often called limonite, $Fe_2O_3 \cdot nH_2O$; and magnetite, $FeO \cdot Fe_2O_3$. Hematite occurs in a scaly black micaceous form (specularite), as massive red-black hematite, in fibrous masses, and as the powderous red ochre. The compact varieties have a hardness of 5.5-6, but the earthy forms are soft. The luster is submetallic to dull or earthy, and the streak is reddish brown. Limonite occurs as compact, fibrous, or earthy porous masses. Its color is yellow to brown, and its streak is yellowish-brown. The luster of limonite is usually dull or earthy, but some fibrous limonite is submetallic to silky.

Both limonite and hematite are iron ores, but the principal role in the more common rocks is that of pigmentation. Very minor quantities of limonite or hematite cause discoloration in rocks. Indeed, these minerals are the pigment in most rocks of brown, buff, or red tints. Magnetite is black and has a hardness of 5.5-6.5.

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## CHAPTER III

# ROCKS, AN INTRODUCTION

MORE THAN HALF A CENTURY AGO, IN A PREFACE TO THE widely known text *The Materials of Construction*,[1] it is stated:

> The rational designing of any kind of construction involves a knowledge of:
>
> The external forces to be resisted, transformed, or transmitted,
> The internal stresses resulting therefrom;
> The mechanical properties of materials to be employed to accomplish the object sought.
>
> Of these three coordinate departments of knowledge the first two are founded on the sciences of mathematics and applied mechanics. The last one, however, does not rest on any deductive science, as this information can only be gained by patient, expensive and competent research.

Because a civil engineer deals with earth materials in almost every construction job ever undertaken, it is essential that he know something about their properties, structure, and occurrence. Every engineering structure must rest on something, and for many, excavations must be made. In many projects earth materials are employed as building blocks, aggregates for concrete or mortar work, or as loose earth. Consequently, cost, stability, and in some instances feasibility of engineering projects are in greater or lesser measure dependent on the strength, structure, and accessibility of the earth materials concerned.

Broadly speaking, rocks are aggregates of minerals. The chief

[1] Johnson, J. B., *Materials of Construction*, 1st. Ed., N. Y., 1897.

exceptions are the rock glasses and coals. The term includes not *only those of coherent, or consolidated character, but also the unconsolidated and uncemented materials which occur as clays, sands, gravel, and other less common and less familiar types. The properties of rocks, their structures, modes of occurrence, and present form* are dependent upon the environments in which they originated and by which they have been subsequently affected.

### THE MAJOR DIVISIONS OF ROCKS—"THE ROCK CYCLE"

Rocks that have solidified from a molten solution are called *igneous* rocks. Igneous rocks have been formed beneath the earth's surface to unknown depths. They have also been formed, and are forming at the present time, by the consolidation of lavas extruded upon the earth's surface. Once the igneous rocks reach the earth's surface, either through volcanic action or by the wearing away of the overlying materials, they are subjected to an environment quite different from the one in which they formed. At or near the surface they are subject to attack by superficial agents such as water, oxygen, carbon dioxide, and temperature changes. The most durable rock eventually yields to the attack of these agents. The collective processes of rock disintegration and decay are termed *weathering*. When rocks have been weathered into loose material, they are subject to removal by wind, water, ice or organisms. If they are moved, they must eventually come to rest again, giving rise to *sedimentary* rocks. During weathering and removal, some portions are transported in solution which may subsequently give rise to precipitates forming sedimentary beds, veins, cements in fragmental materials; or they may remain in solution, as illustrated by the salts of the sea.

Once having formed from molten rock solutions or through the processes of sedimentation, a new environment of heat, pressure, or both may be imposed upon the rock, with transformations attending the change. Rocks thus altered and changed from their original igneous or sedimentary form are called *metamorphic* rocks.

It is at once obvious that sedimentary deposits may be subjected anew to weathering, transportation, and redeposition, forming a sec-

ond generation of sediments. Some sedimentary rocks have evidently gone through such a cycle not once but several times. It is equally apparent that rocks already metamorphosed may be resubjected to overpowering stresses or heat resulting in further changes. To state it simply, metamorphic rocks can be metamorphosed. If sufficient heat is developed, melting of any of the rock types may take place, an action which gives rise to new igneous rocks. This remelting of rocks is probably of limited and local importance. The sequence of

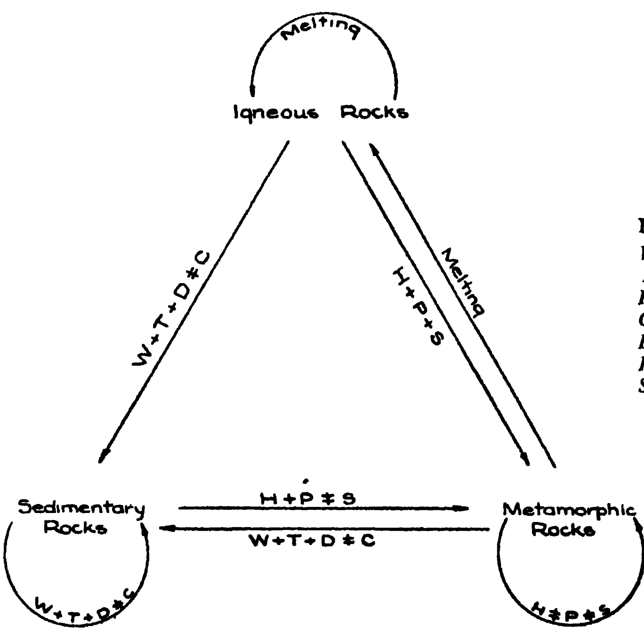


Fig. 3-1 The rock cycle
W, weathering
T, transportation
D, deposition
C, consolidation
H, heat
P, pressure
S, solutions

events just described constitutes what is known as the rock cycle, diagrammatically shown in Fig. 3-1.

The geologic map Fig. 3-2, illustrates a common association of the three major rock groups. The sedimentary rocks were deposited in the sea, and after solidification they were folded. A hot liquid solution of rock materials (magma) from within the earth was then forced into the folded sediments. The magma was sufficiently hot to alter the sedimentary rocks with which it came in contact, thus forming a metamorphic aureole, or ring of metamorphic rocks about

the intrusion. Because rocks are poor conductors of heat, the metamorphic aureole is of relatively limited extent. After the liquid rock had cooled and crystallized into solid form, the agents of erosion gradually wore down the area, exposing the igneous rock, as shown by the cross section accompanying Fig. 3-2.

A fourth major group, composed of rocks of mixed origin, is

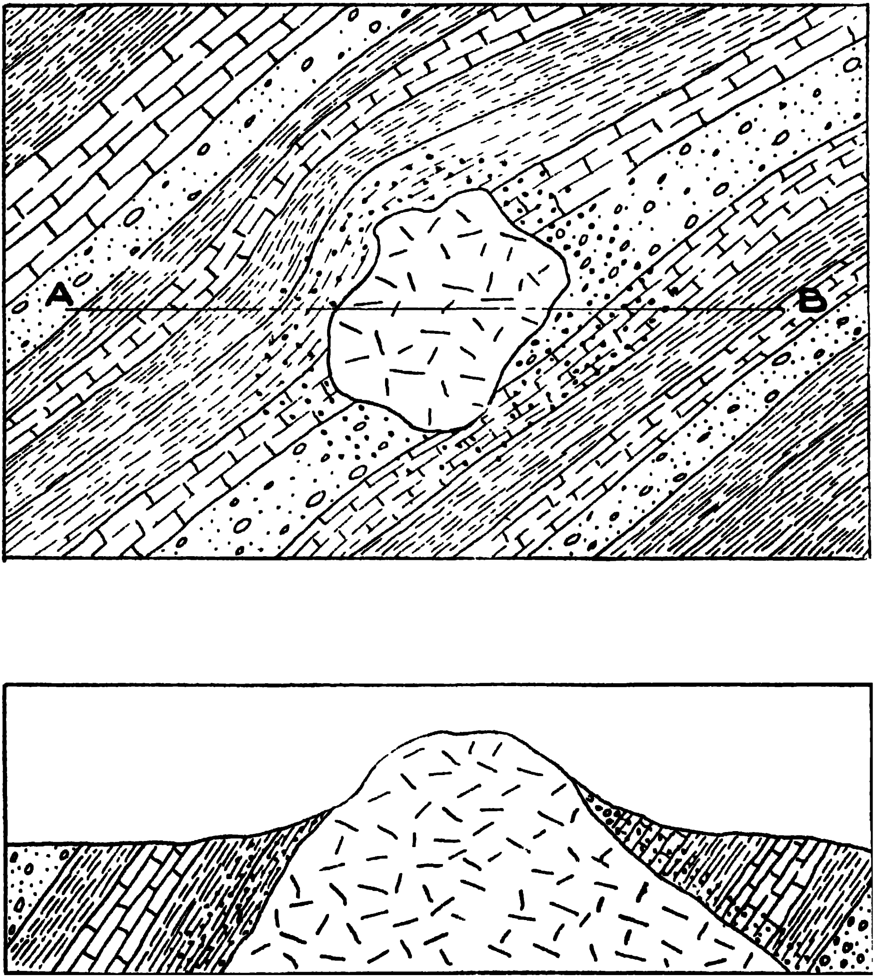


FIG. 3-2. Association of the three major rock groups. The intrusive mass in the central part of the map has penetrated a folded series of sediments; the sediments abutting on the intrusion have been metamorphosed.

recognized by many geologists. In some areas, the penetration of igneous rock into host rock is so intimate as to defy separate mapping of the host rock and the invading rock. The host rock may be either metamorphic or igneous. Rocks of this mixed type are called *migmatites.*

### Distribution of the Major Rock Types

While any generalization of geographical distribution of the major rock types is contradicted by exceptions, some conclusions seem to have at least a measure of validity. The plains areas of the world are, for the most part, underlain by sedimentary rocks in essentially horizontal position. In these areas, very few igneous rocks are known to have penetrated the sediments. Metamorphic rocks are likewise virtually absent. Metamorphic and igneous rocks outcrop widely in the highly deformed mountain belts of the earth where erosion has bitten deeply enough to expose the intrusive masses. Active volcanoes and recent volcanic lavas are associated with mountains of recent date. The products of ancient volcanism, correspondingly, are widely distributed in old worn-down mountain zones. Lava flows of wide extent are present also in some of the great plateau regions of the world, associated with faults or breaks in the earth's crust.

Each continent has its nucleus of very ancient and highly deformed metamorphic rocks and associated igneous rocks. The geologic map of North America, for example, shows the generalized distribution of the three major rock groups. The old mountain zone along the Appalachian belt is clearly discerned. The central core or nucleus, called by geologists the *Canadian Shield,* also stands out prominently, as does the western mountain area. Between the Appalachians and the Rocky Mountains, the broad expanse of sedimentary rocks is broken only by a few island-like exposures of the old crystalline basement on which the sediments were deposited. In summary it may be stated that the igneous and metamorphic rocks are largely confined to the intensely disturbed areas, the mountain zones of present or past days. The sediments characterize the plains; and lava flows and sediments make up the plateaus.

Approximately 80 per cent of the earth's land surface is covered with a veneer of sedimentary deposits. The remaining 20 per cent of the land surfaces are underlain by igneous and metamorphic rocks. But the sedimentary deposits are relatively thin, and of the outer portions of the solid earth to a depth of 10 miles, igneous rocks make up about 95 per cent.

## Uses of Rock

Besides serving as natural foundations upon which all engineering structures rest, rock is used as a structural material in various ways.

***Dimension Stone.*** Cut into blocks, stone is used for building material both for interior and exterior purposes. Interior uses include floor tiles, steps, banisters, paneling, fireplaces and mantels, toilet inclosures, and other applications. Exterior uses include building walls, bridges, dams, retaining walls, sea defenses, docks, and other structures where strength, durability, and architectural effect are desired.

Building stone is classed as cut or finished stone, ashlar, rough building stone, and rubble. Finished stone is for the most part shaped according to specifications, as for corner, window, or cornice applications, and the like. *Ashlar* refers to small rectangular blocks which in contrast to cut or finished stone are not accurately sized or surface finished. Rough building stone consists of various shapes and sizes of blocks, whereas *rubble* is a term applied to irregular or angular material having but one good face. Dimension stone is also used for monuments. Stone monuments vary in size and complexity from such a structure as the Washington monument to a simple foot-marker in a cemetery. Paving blocks and curbing are more durable than concrete and, in certain areas subjected to extremely heavy traffic, are preferable to any other surfacing.

In the selection of dimension stone, the obvious properties of color, texture, and physical appearance of the stone must be taken into account, as well as its durability and physical properties. Ac-

cessibility, workability, and cost are additional factors which must be considered for any type of rock use.

***Crushed Rock.*** Crushed rock is used widely in the construction of highways and airports as base material and in the surface courses, and in the fabrication of concrete. Soundness, durability, and wear resistance are the important properties to note in selection of rock for crushing.

***Raw Material for Structural Products.*** In the manufacture of structural products, rocks are of importance. Brick, tile, cement, and plaster are illustrations of construction materials manufactured from clay, limestone, and gypsum. Paints, roofing granules, rock-wool, and many other rock and mineral products are used in the construc tion trades, but their study falls more properly in the realm of *economic geology.*

## Physical Properties of Rocks

The physical properties of rocks are, for the most part, readily determined in the laboratory. The specific use for which a rock is being considered determines what properties and consequently what tests are of significance. In the following discussion, the physical properties most directly related to strength are first described, followed by a brief discussion of certain other properties of engineering significance.

***Strength.*** The properties of rock, such as resistance to crushing, flexure, shear, impact, and abrasion, depend in a large measure upon the texture of the rock and the nature of the bond between the individual mineral particles making up the rock. The mineral composition, likewise, has an important influence on these properties. Another factor should be mentioned, also, and that is the structure of the rock specimens undergoing tests. Many, if not most, rocks have structural planes present which give rise to differences in test results according to the orientation of the test blocks. These features are described in more detail in subsequent discussions of rock structure. Especially to be noted, however, in connection with strength tests are:

1. *Rift* and *grain* in granites and similar rocks
2. *Bedding* or *stratification* in sediments
3. *Foliation* or *schistosity* in the metamorphics

All of these properties are well known to stone workers and are utilized in shaping dimension stone. In recording results of mechanical tests on rock specimens, it should be the general practice to record also the structural position of the test specimens. Fig 3-3 illustrates this point. It has been found, for example, that the compressive strength of granites may vary as much as 12 per cent according to the orientation of the test specimen. Consequently in laying stone, particularly in positions where loads are heavy, good practice seems to call for the direction of easiest parting, the bedding planes, or foliation planes, to be placed normal to the maximum stress.

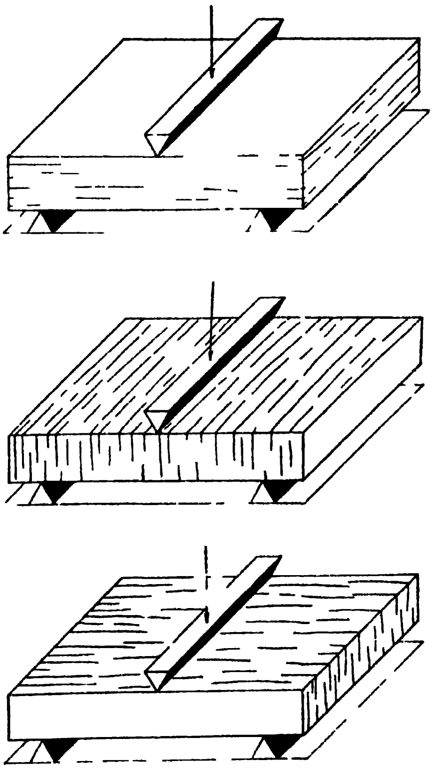

FIG 3-3 Positions of test specimens with respect to structure

*Crushing Strength.* The crushing strength of consolidated, sound rock, suitable to the job in other respects, does not commonly enter into consideration. Virtually all sound types have crushing strengths far in excess of any loads which may be placed upon them. The Washington monument for example, exerts a pressure on its foundations of about 315 pounds per square inch. Most sound rocks give crushing strengths of more than several thousand pounds per square inch. A safety factor of 20 is usually demanded, and hence a crushing

strength of 5000 to 6000 pounds per square inch would ordinarily be satisfactory. The crushing strength of concrete commonly ranges from 2500 to 4000 pounds per square inch. The crushing strength of the crystalline rocks (igneous and metamorphic) is commonly in excess of 5000 pounds per square inch, and may run as high as 60,000 pounds per square inch. Table B of Appendix II shows the relative compressive strengths of various rock types. It should be noted, however that this test assumes more importance when dealing with some types of sediments not completely consolidated or indurated.

*Flexural Strength.* Flexural strength or resistance to bending is measured in terms of the modulus of rupture computed from the formula:

$$R = \frac{3Wl}{2bt^2}$$

in which $W$ is the load, at the middle of the span, required to produce rupture; $l$, the distance between supports; $b$, width of the specimen; and $t$, thickness Because stone in modern construction is not ordinarily subjected to high bending stresses, the modulus of rupture is not customarily determined The settlement of buildings, however, may induce such stresses, and failures have resulted because the stone used was too weak in transverse strength to resist the deformation. The modulus of rupture of concrete commonly ranges between 600 and 900 pounds per square inch Comparative results of tests determining the modulus of rupture for different kinds of rôck are shown in Table E of Appendix II.

*Shearing Strength.* The shearing strength of stone used in large structures may become important as a result of improper masonry which sometimes results in concentrating large loads near the edges of the blocks. Shear failure sometimes results in spalling Kessler, Insley, and Sligh[3] describe shearing tests used at the Bureau of Standards and figure the punching shear device used for the tests.

[3] Kessler, D. W, Insley, H., and Sligh, W H, "Physical, Mineralogical and Durability Studies on the Building and Monumental Granites of the United States," *U. S. National Bureau of Standards Research Paper R P 1320,* 1940, p. 187.

Comparative shearing strengths of several rock types are shown in Table D of Appendix II. The shearing strength of concrete commonly ranges from 1250 to 2000 psi.

*Toughness and Abrasion Resistance.* The resistance of a rock to impact, i.e., its tenacity, defines its toughness. This property is particularly important where the rocks are subjected to severe use and impact—for example, the grinding of pebbles in a ball mill or some types of highway surfacing. Toughness is tested by means of an apparatus designed to drop known weights through measured distances onto the test specimen. The comparative toughness of a number of different rock types is shown in Table G of Appendix II. This table also describes a test used for toughness.

It is desirable in some instances to determine the resistance of a rock type to abrasion. There are various methods for estimating this property. The National Bureau of Standards method involves grinding specimens 2 by 2 by 1 inch under a pressure of 2 kilograms on a cast-iron grinding disk to which artificial corundum is fed at a constant rate. The abrasive hardness $H_a$ is computed by the formula:

$$H_a = \frac{10\,(W_s + 2000)G}{2000W_a}$$

in which $W_s$ is the original weight of the specimen, $G$ its bulk density, and $W_a$ the loss in weight after grinding (all weights in grams). Table H of Appendix II shows comparative hardnesses of several rock types. Toughness and abrasion resistance are important factors in quarry production costs, for upon them, in considerable measure, depend the ease or difficulty of drilling, blasting, and crushing.

***Other Engineering Properties of Rock.*** Certain other properties of rock are of engineering importance and for some work are of paramount significance. For example, in engineering practice it is frequently necessary to measure or estimate density, absorption, porosity and permeability, heat resistance, and durability.

***Density.*** The bulk density of rock is determined by taking dry

weight of a specimen and its suspended weight in water after prolonged soaking The density is expressed by the formula

$$D_b = \frac{W_1 d}{W_2 - W_3}$$

in which $W_1$ equals dry weight, $W_2$ equals weight in air after prolonged soaking, $d$ is the density of the water, and $W_3$ equals the suspended weight in water after prolonged soaking The true density of the rock can be determined by the use of either the Le Chatelier flask or the pycnometer Because of the low porosity of most igneous and metamorphic rocks, the bulk and true densities are but slightly different, and for these types a determination of the bulk density usually suffices

*Absorption* The determination of absorption is made on specimens that have been previously dried and then immersed for various lengths of time The absorption is computed by the formula

$$A = \frac{W_2 - W_1}{W_1} \times 100$$

where $W_1$ is dry weight and $W_2$ the weight after soaking The absorption of the crystalline rocks (those with closely interlocking mineral grains, such as the metamorphics and most of the igneous rocks) is commonly low, and their resistance to the disintegrating effects of frost is correspondingly high Some representative absorption values are given in Table I of Appendix II.

*Porosity and Permeability* Porosity and permeability of rocks are closely related properties, for without openings of some sort there can be no passage of fluids through the rock. The two properties, however, must always be clearly distinguished.

The *porosity* of a rock is defined as the percentage of total volume occupied by pore spaces Porosity is not directly related to absorption, although it is true that rocks with low porosity have relatively low absorption. The igneous rocks, with the exception of a few types, and the metamorphic rocks have very low porosity. Many sedimentary rocks have a large porosity, and in some the pore spaces may occupy as much as 50 to 75 per cent of the total volume. Deter-

mination of the porosity of consolidated rocks can be computed from the bulk density and true density values by the formula:

$$P = \frac{(D_a - D_b)}{D_a} \times 100$$

in which $D_a$ is the true density, and $D_b$ is bulk density. Some representative porosity determinations are given in Table J of Appendix II. A discussion of porosity of unconsolidated sediments is deferred to a subsequent consideration of those materials.

The permeability of rocks is particularly important in a number of engineering problems, for example those dealing with foundations for dams, reservoir areas, certain sanitary engineering problems, and the building of walls and other structures, where water transmission is of importance. *Permeability* is defined as the capacity of a substance to transmit a fluid. As emphasized previously, permeability must be distinguished from porosity. Rocks may have a high porosity, and yet, because the openings are not connected or because the connections are of small size, the transmission factor may be very small. Most igneous and metamorphic rocks are relatively impermeable, as are the very fine textured sediments. Certain of the igneous rocks, some sediments, and some calcareous metamorphic rocks, however, are readily permeable.

*Heat Resistance.* Most rocks are seriously damaged by fire if the temperatures reach about 850° C. A series of tests by W. E. McCourt indicates that, in general, sandstones suffer the least damage, followed in order of decreasing resistance to damage by fine-textured granite, limestone, coarse-textured granite, gneiss, and marble. The limestones and marbles begin to calcine between 600 and 800° C., and are ruined at temperatures above 900° C. The chilling effect of a stream of water played on heated rock, as often observed, accentuates the fire damage.

*Durability.* Some rocks contain minerals, such as pyrite, which, when exposed to the atmosphere, deteriorate, leaving pits or causing disfiguring stains. Other rocks because of their composition may be unsatisfactorily durable. The durability of rock can best be esti-

*mated by observing outcrops of the rock in the vicinity of the quarry and by examining quarry waste piles. Another obvious method is to observe the condition of the stone in structures that have been* exposed to the weather or have been in use over a period of years. Some rocks, because of their susceptibility to frost action, are not suited to outside uses in the cooler climates. Rock durability depends in large measure also upon the nature of the bond between the mineral constituents. For example, sandstones with admixed clay have failed in some instances to give satisfactory service because of slaking effects on the clay

In general, it may be said that, barring fire, the crystalline rocks, both igneous and metamorphic, and the thoroughly cemented and well-indurated sedimentary rocks of low absorption are satisfactorily durable.

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Courtesy of Spence Air Photos

VOLCANIC CINDER CONE. (AMBOY CRATER, CALIFORNIA.)

CHAPTER IV

# IGNEOUS ROCKS

OF THE THREE MAJOR ROCK GROUPS, THE IGNEOUS ROCKS constitute the major portion of the solid part of the earth, at least in the outer zone. From this group, as has already been indicated, are derived the metamorphic and sedimentary rocks.

Igneous activity can be subdivided into two main classes: (1) subsurface movements, or intrusive activity; and (2) surface movements, or extrusive activity. It is obvious, of course, that the molten lavas which issue at the earth's surface through rents or openings had their origin beneath the surface and have moved radially outward. There is thus a gradation or connection between intrusive and extrusive action. The significance of the terms *intrusion* and *extrusion* as applied to molten rock masses is made readily apparent by a simple analogy. A toothpaste tube can be squeezed causing *extrusion* of the paste. If, however, the mouth of the tube is inserted into a dish of gelatine and then squeezed, the paste is *intruded* into the gelatine, making room for itself by crowding the gelatine aside. Some geologists have classified igneous rocks into the following three groups: deep-seated, or *plutonic;* intermediate, or *hypabyssal;* and shallow, or *extrusive.*

## CRYSTALLIZATION AND TEXTURE

As the temperature of the magma, or molten rock solution, drops, crystallization is initiated. The order of crystallization is the order in which mineral components become insoluble in the rock solution. Careful studies of a good many igneous rocks have estab-

lished the very common order of crystallization of the common rock-making minerals

ORDER OF CRYSTALLIZATION OF ROCK MAKING MINERALS

| | | |
|---|---|---|
| *Early* | Olivine | |
| | | Lime feldspars |
| | Pyroxene | |
| | Amphibole | |
| | | Soda feldspars |
| | Biotite | |
| | Potassium feldspar | |
| | Muscovite | |
| | Quartz | |
| *Late* ↓ | | |

(After Bowen)

The size and arrangement of the crystals composing the igneous rocks define the property known as *texture*. Certain of the rocks which hardened without crystallizing are said to have a glassy texture. Crystallized igneous rocks show a variety of grain sizes and arrangements. These gradations may be expressed in terms of the size of grain as follows:

| | |
|---|---|
| Very coarse | More than 3 cm |
| Coarse | More than 5 mm |
| Medium | 1 to 5 mm |
| Fine | Less than 1 mm |
| Dense | Individual minerals too small to be distinguished without magnification |

Two other textural varieties should be mentioned. The first of these is *pegmatitic texture,* which is a coarse, very irregular type of crystallization. In rocks displaying the pegmatitic type of texture, individual constituents may vary in size from a small fraction of an inch to several feet. Exceptionally, mineral crystals occur with a maximum dimension of 20 feet or more. The chief characteristic is irregularity. *Porphyritic texture* should also be defined. This texture consists of relatively large crystals included in a *groundmass* or *matrix* of relatively finer texture. However, it should be understood that the groundmass of the crystalline rocks may be very coarse,

coarse, medium, fine, dense, or uncrystallized with glassy texture. The larger crystals scattered through the matrix vary from a small fraction of an inch in diameter in some of the rocks of fine or dense groundmass, to several inches in the rocks of medium or coarse textured groundmass. The larger crystals are termed *phenocrysts* and the igneous rocks containing phenocrysts are called *porphyries.*

FIG. 4-1. Porphyritic granite, Goudreau, Ontario. Groundmass has grains about one-eighth inch in diameter. About one-half natural size. (F. F. Grout)

Fig. 4-1 shows a prophyritic texture. Prophyritic texture is commonly explained as the result of two stages in cooling. Crystallization may have started at depths where conditions of slow cooling prevail; then if the magma is forced into a cooler environment, the remaining liquid portions crystallize more rapidly, thus giving rise to the groundmass.

***Conditions Influencing Texture.*** Slow cooling and crystallization

of the magma result in coarse textured rocks. Relatively few centers of crystallization are established in this case, and sufficient time permits the atoms to arrange themselves in relatively large crystals. Rapid cooling, on the other hand, favors the initiation of many centers of crystallization, and the finer textures result. It is frequently observed that the margins of intrusions display finer textures than the interiors, a result of the more rapid cooling at the contacts. If, however, the adjacent rock was preheated or movements within the liquid magma were active enough to prevent marginal crystallization until the wall rocks had become heated, coarse textures may prevail right up to the margin.

Another very important textural factor, however, is the presence of certain substances in solution, notably water, boron, fluorine, chlorine, sulphur, and carbon dioxide, all of which are termed mineralizers. These substances reduce the viscosity of the solutions and prolong the consolidation interval, thus promoting a coarser crystallization than would otherwise develop. The coarse and notably irregular texture of pegmatitic type is caused by an abundance of mineralizers.

## Classification of Igneous Rocks

The intrusive igneous rocks are grained with the exception of very small intrusions and some thin marginal selvages. They are classified according to texture (Table 4.1), minerals present (Table 4.2), and chemical composition. Chemical analyses, of course, are not commonly available, but color permits a rough classification as to chemical types. The light-colored varieties are commonly acidic; the dark-colored rocks, basic. The intermediate colors indicate intermediate chemical composition. The term *silicic*, or *salic*, applied to a rock, means a relatively high silica content, whereas *mafic* means relatively rich in iron and magnesium. Practically, however, the rock name is determined by the minerals which are present and by the texture. Especial attention should be called to the distinction between the feldspars, for they form the true basis for the classification of igneous rocks.

TABLE 4.1. A FIELD CLASSIFICATION OF THE IGNEOUS ROCKS

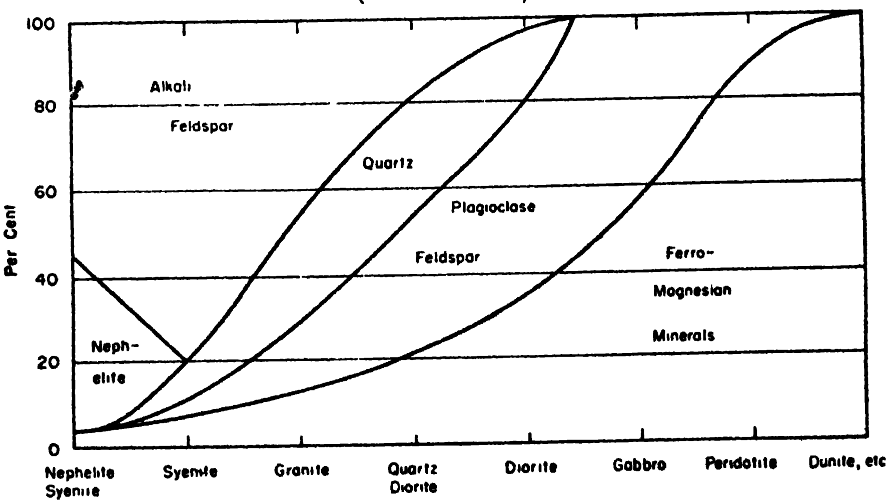
| | Light | Intermediate | Dark | |
|---|---|---|---|---|
| Texture | Quartz and feldspar, other minerals minor | Feldspar and hornblende | Augite and feldspar | Augite Hornblende Olivine |
| Very coarse irregular | Pegmatite | Diorite Pegmatite | Gabbro Pegmatite | |
| Coarse, medium, and fine | Granite, or aplite if light sugary texture, of fine grain | Diorite | Gabbro or dolerite if fine grained | Peridotite |
| Dense | Felsite | | Basalt | |
| | Rhyolite | Andesite | | |
| Glassy | Obsidian (if very vesicular, Pumice) | | | |

Any of the types may have porphyritic varieties

The feldspar of the 'light' rocks in this table is dominantly microcline or orthoclase, the feldspar of the 'intermediate' and 'dark" rocks in this table is dominantly plagioclase

Rocks composed of volcanic ejected fragments are *breccia* (coarse) and *tuff* (fine)

TABLE 4.2. MINERAL COMPOSITION OF INTRUSIVE IGNEOUS ROCKS (After Pirsson)



The volcanic rocks are for the most part of fine, dense, or glassy texture. Fragmental volcanic rocks are the results of violent explosion and may be composed of materials of any of the above-mentioned textures. Occasionally, thick flows of extrusive rocks are found to have locally somewhat coarser textures than normally displayed. In the field classification of rocks (Table 4.1), it will be noted that color rather than mineralogical composition is the determining factor in naming the dense rocks. Chemical analyses have shown that lavas displaying various shades of red, brown, green, and gray commonly correspond to the acidic and intermediate intrusive rocks. Only lavas of very dark color correspond to the basic intrusives. Hence the twofold division of the dense rocks seen in Table 4.1. If the volcanic rocks are porphyritic, the geologist is frequently able to make more refined distinctions than are presented here For practical purposes, however, this classification is adequate. Strictly speaking, the volcanic tuff and agglomerate of Table 4.1 might be better considered sediments. They are, in part, water laid, as volcanic ejecta frequently settle in bodies of water.

### The Intrusives

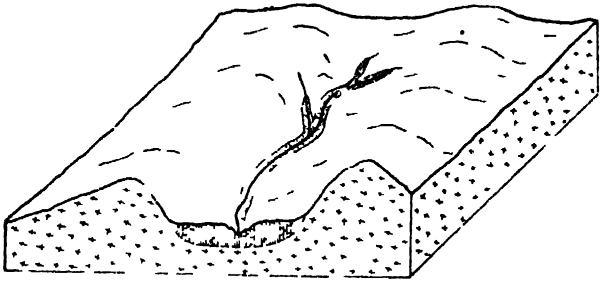
The intrusive igneous rocks, as stated, are those that have solidified from molten rock solutions called *magmas* which have penetrated other rocks. These intrusions vary in size from very minute occurrences to masses hundreds of miles in extent. They may penetrate sedimentary, metamorphic, or other igneous rocks.

***Modes of Occurrence.*** It is convenient to classify the intrusive igneous rocks according to their modes of occurrence. The mode of occurrence means the manner, shape, or form in which the igneous rock mass occurs.

*Batholiths* (Fig. 4-2). A batholith is a large mass of igneous rock which has crystallized at some considerable depth below the earth's surface and is exposed only by erosion. The great Sierra Nevada Range is, in large part, a great batholith; and many other examples of huge areas underlain by intrusive rocks of this mode of occurrence

could be cited. The depth to which batholiths may extend is unknown, and the nature of the lower portions of batholiths is subject to debate. Certain it is that they extend to great depths; and if the lower limits of any batholith have ever been exposed by erosion, it has escaped recognition. In British Columbia, the intrusive rocks of the Coast Range batholith show no significant differences from the crests of peaks 15,000 feet high to the lowest valleys incised in the rock nearly to sea level.

Fig. 4-2. Eroded batholith. The roof has been entirely eroded away except for the central valley.



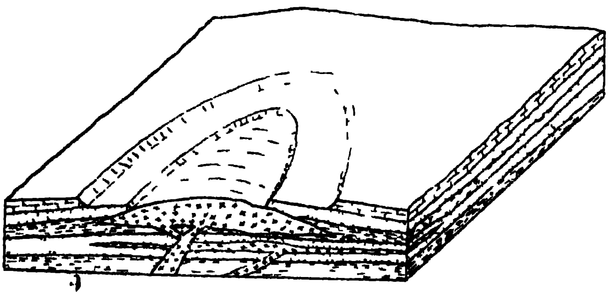


Fig. 4-3. Eroded laccolith with sills and dikes.

*Stocks or Bosses.* Areas of igneous rock, often of more or less circular outline, exposed by erosion over an area of less than 30 to 40 square miles are commonly called *stocks* or *bosses*. These may be in part protrusions from an underlying batholith not yet exposed, or they may be independent intrusions. These, like the batholiths, have unknown, but great, downward extent.

*Laccoliths* (Fig. 4-3). Intrusions which have penetrated stratified rocks as lenses causing an up-arching of the roof are called *laccoliths*. They vary in size from a few hundred yards to several miles in

diameter, and from a few hundred feet to several thousand feet in thickness.

*Sills* (Fig. 4-3). Intrusions of magma between the bedding planes of sedimentary rocks or the structural planes of metamorphic rocks are called *sills* or *sheets*. These in general have relatively slight thickness as compared with their other dimensions. They vary in size from a fraction of an inch to several thousand feet in thickness and proportionately in other dimensions. They may be either horizontal, inclined, or vertical in attitude, depending upon the attitude of the structural planes into which they were forced. A laccolith may be considered in effect a locally thickened sill.

*Dikes* (Fig. 4-3). Tabular-shaped intrusions, relatively elongated, that cut across the stratification of sediments, structural planes of metamorphic rocks, or penetrate other igneous rocks are called *dikes*. Dikes show variations in dimensions on the same order of magnitude as those just mentioned for sills, and like the sills also they may vary in attitude from vertical to horizontal.

***Mechanics of Intrusion.*** One of the major problems concerned with igneous rocks is the question of how the magmas made room for themselves. For laccoliths it is at once apparent that this space was achieved by actual lifting of the overlying beds. The same mechanism also explains the intrusions of most sills. Many dikes are fracture fillings, and in the intrusion of most dikes, probably the fractures have been enlarged by the hydraulic action of the magma being forced in under pressure. For the larger intrusions such as batholiths and stocks, however, it is difficult to explain what has actually taken place. The Coast Range batholith of the Pacific northwest, for example, has a linear extent of perhaps 1200 miles and an average width approaching 70 miles. Its depth is unknown, but it must be great. Hence a volume of magma of a good many thousand cubic miles has forced its way up into the crust, where it could be exposed by erosion. What has become of the rock which formerly occupied the space now taken up by the granite? Detailed structural work on intrusions and the surrounding rocks suggests that various

methods have been utilized by the magma to make a place for itself. Some magmas in their ascent from the depths to the outer portions of the earth's crust may have a measure of superheat, i.e., heat in excess of that required to keep the magma fluid. Insofar as this is true, a magma may actually melt or assimilate the adjacent rock. Superheat is soon lost, however; and it is probable that this process has been only locally effective, at least in the zone in which the magma came finally to rest. How much deep-seated or abyssal assimilation may have taken place is uncertain. Instead of by actually melting the adjacent rock, the magma may react with it. Assimilation of this type does not require the superheat postulated under the assumption of pure melting. The clean-cut margins of many large intrusions, however, indicate that reaction with the wall rock is of limited extent, at least in the zone of final consolidation. In the study of some igneous bodies, banding suggestive of sedimentary bedding is recognized. Relic structures of this type indicate that some igneous bodies have been formed by the invasion of igneous emanations, aqueous or gaseous, replacing the invaded rock masses volume for volume, in a way analogous to the petrification of wood.

The contacts of some large intrusions are very blocky and, in some, many fragments of the adjacent rocks are found imbedded in the igneous mass. This suggests that the magma has forced its way into cracks in the adjacent rock and actually pried or broken off chunks of the rocks being invaded. This process of natural quarrying by magmas is termed *stoping*. Some dikes have also been emplaced, at least in part, by this method.

Around the margins of some intrusions, both large and small, the adjacent rocks have been deformed by the thrust of the magma, suggesting an actual forceful injection, space being made for the liquid by shouldering aside the wall rock. The direction of easiest relief determines the direction of magma movements; and the nature of the adjacent rock, under the conditions of temperature and superincumbent load prevailing at the time of intrusion, determines the character of the deformation.

***Structures.*** The intrusive rocks display structures which were determined at the time of congelation of the magma and immediately following, and structures that have been subsequently imposed upon the igneous mass. The first group of structures related to the intrusive or late magmatic stages are termed *primary* structures. Those that have been subsequently imposed are termed *secondary* structures. It is fortunate for man that the igneous rocks contain these structural features, since by their presence quarrying is facilitated.

If the magma started to crystallize before movements of the liquid ceased, *flow structures* may record the movements. These flow structures are divisible into two primary classes: (1) planar-flow structure, and (2) linear-flow structure. Planar-flow structure is marked by the parallelism or alignment of minerals in a plane. The common minerals showing the plane structure are those that have one relatively small dimension. Very commonly the micas are drawn into parallelism by magmatic movements so that their cleavages are parallel. Feldspar phenocrysts also frequently display a similar arrangement and mark out the plane of flow. Irregularities in composition, as for example zones richer in dark- or light-colored constituents called *schlieren,* may also mark the structure.

Linear-flow structure may be developed where minerals or inclusions having one relatively long and two relatively short dimensions are present previous to the cessation of magmatic movement. These may be drawn into parallelism by the flow. Hornblende needles, mica streaks, and cigar-shaped inclusions commonly constitute the lineation. Lineation marks the direction of magmatic currents prior to consolidation. The arrangement of the linear elements may be likened to the orientation of logs floating in a stream, directed by the currents. Where both planar and linear flow structures are present, it is found that the lineation lies in the plane of the planar flow structure. However, either of the types of flow structure may occur singly. The flow structures may be vertical or inclined at varying angles. They are, in general, parallel to the nearest friction-exerting surface.

Well known to stoneworkers and quarrymen is the tendency of many igneous masses to split more readily in two directions than others. The direction of readiest parting is called the *rift,* which is commonly either nearly vertical or nearly horizontal. The direction of next easiest parting is called the *grain.* The direction of most difficult parting, usually at right angles to both rift and grain is known by stoneworkers as the *"hardway".* In part, rift and grain are due to the parallelism of feldspars and micas. In addition, microscopic or submicroscopic cracks in the quartz and feldspars and sheets of tiny fluidal cavities in quartz are factors. Rift and grain are not always parallel to the flow structure. Stresses within the rock mass during and following the final consolidation probably account for rift and grain. Whatever their origin, rift and grain have been most important economic factors in granite quarrying and working from ancient times to the present.

FIG. 4-4. Porphyritic granite with flow structure. The smaller of the two white objects at top of picture is two and three-quarters inches long. The feldspar phenocrysts are roughly aligned.

As cooling and crystallization progress, the magmas become increasingly rigid and ultimately are subject to cracking. Inasmuch as the linear-flow structures show the direction of easiest relief and elongation of the liquid mass, the plane normal to the lineation is subject to tension. If the same stress set-up prevails in the late magmatic stage, *tension joints* develop that stand normal to the linear flow structure. Since at the time of their development there may be residual liquid still present, many of the tension joints are filled with the liquid residue in the form of narrow dikes. As would be expected from the normal order of crystallization,

which has already been pointed out, many of these tension joint fillings are comprised essentially of quartz and feldspar. In Fig. 4-4 is shown a photograph of granite with a planar structure marked by the alignment of the feldspar phenocrysts.

The second group of structures, those imposed on the mass after final consolidation, are the secondary structures. Joints, shear zones, and faults are the chief structures of this class. In the large intrusive masses probably the most widely developed, conspicuous, and economically important structural feature is the sheeting, as illustrated

FIG. 4-5. Sheet jointing in granite on Mosquito Mountain, Frankfort, Maine.

in Fig. 4-5. Sheeting joints tend to follow the erosion surface and hence commonly dip quaquaversally about hills. It is noteworthy that the sheet joints are more closely spaced near the surface and become spaced progressively farther apart in depth. They are seldom entirely regular and, followed out, commonly terminate against other sheeting joints thus forming large lenses. In part, sheet jointing may be related to surficial temperature changes; but in a large measure it appears to be due to expansion of the mass as the overlying body of rock is eroded away. Other joints, vertical or inclined, are usually present. These are generally quite regular in spacing and attitude. Where the joint spacing is too close, quarrying for dimension stone is impossible.

Shear zones, or zones of closely spaced joints along which slight movements have occurred, may be present occasionally as the result of overpowering stresses. Faults, or breaks along which differential movements have occurred, are not infrequently found in igneous rocks. If dikes or sills are faulted, the displacement may be readily apparent. Faults in the large intrusive masses, however, are more difficult to recognize because of the absence of markers by which the displacement may be distinguished. Shear and shatter zones in the massive igneous rocks, both those along which considerable movement has occurred, as well as those along which there has been a minimum of movement, may be loci of ready water penetration and weathering.

***Intrusive Rock Types.*** The intrusive rocks may be divided into a number of types, examples of which are granite, syenite, or diorite.

*Granite.* The most common intrusive igneous rock is *granite.* Granites are composed essentially and dominantly of quartz and potassium feldspar and hence are light-colored. A sodic plagioclase is commonly present in some abundance. Dark minerals, which are virtually absent in some varieties of granite, seldom exceed 25 per cent by volume of the rock. Biotite is perhaps the most common subordinate mineral. Muscovite and hornblende are also frequently present. Common, but less abundant and less conspicuous, may be pyrite and the iron oxides, hematite and magnetite. Locally developed, commonly near roof or walls, tourmaline and garnet may be found in some abundance. The textures of the granites show a considerable range, varying from fine to very coarse. Porphyritic texture is not uncommon; feldspars commonly comprise the phenocrysts.

Where a flow structure is seen in the granites giving the rock a somewhat banded appearance because of the segregation or parallelism of some of the minerals, notably the feldspars, micas, or hornblende, the rock is said to be *gneissic.*

The granites are named according to the subordinate minerals present. Thus if biotite is present the rock would be termed a biotite granite. If hornblende is present, it is a hornblende granite.

If biotite and muscovite are both present, it would be called a biotite-muscovite granite.

The color of granites varies from very light to medium tones of gray, with various shades of pink to red not uncommon. Occasionally green tints are found. The grain or texture of granites varies from fine to very coarse, and some granites vary markedly in texture within the limits of individual quarries. Commonly, however, the texture and color is uniform for large volumes of rock.

Granites have a low absorption. Tests by the National Bureau of Standards[1] on 90 specimens of granite taken from the eastern states and Wisconsin and Minnesota showed an average absorption of 0.24 per cent for two days' immersion and 0.28 per cent for one year. Of the series tested, not one showed an absorption as great as 0.5 per cent. Computations indicated that the porosity varied for this series of specimens from 0.4 per cent to 3.84 per cent, with an average of 1.29 per cent. The degree of saturation achieved during another series of absorption tests for eastern granites gave an average of 0.66. It can be seen from these porosity and absorption tests that granite has excellent frost resistance. This deduction is borne out by a series of freezing tests on 14 samples of granite from the eastern states and the Middle West.[2] These specimens were frozen 4500 times under conditions similar to those in structures above ground. No sign of disintegration resulted. Previous to freezing the specimens were soaked for two weeks in water, frozen at a temperature of −12° C. for at least six hours, and thawed by immersion in water at about 20° C. for one hour. Frost action, therefore, appears to be negligible in the weathering of granites used for structural purposes.

Because of its mineral composition and interlocking of crystals, granite is hard and abrasion resistant. The compressive strength of granites is variable. Recent tests[3] showed a range from 7700 to 29,700 pounds per square inch with average of 24,500 pounds per square inch in the dry state for 114 samples. From these values, it

[1] Kessler *et al, U. S Bureau of Standards Research Paper, R P. 1320*, 1940.
[2] *Ibid.*
[3] *Ibid.*

can be seen that the granites are amply capable of supporting any load to which they might be subjected in ordinary construction practice with a very large factor of safety. A review of available data shows that the flexural strength of granite expressed as the modulus of rupture varies from 1378 to 3909.7 pounds per square inch. Shearing strength of granite is superior to that of most other building stones and ranges from 3900 to 4600 pounds per square inch. The toughness or tenacity of granite, i.e., its resistance to impact, is somewhat variable and in general inferior to the finer textured crystalline rocks, but superior to that of sandstone, limestone, and marble. The modulus of elasticity for granites is higher than that of any of the other rock types for which data are available. Granite has an average weight of 165 pounds per cubic foot or approximately 2 long tons per cubic yard.

In common with most rocks, granite is subject to spalling and fracture on being subjected to excessive temperatures. Temperatures below 100° C. cause slight damage. Granites are inferior to sandstone in heat resistance, and the coarse grained granites are inferior to the finer textured varieties in resistance to temperature changes.

Some common flaws that impair the value of granite as a dimension stone are the presence of knots and schlieren. *Knots* are dark-colored patches commonly somewhat rounded and of finer texture than the surrounding granite (Fig. 4-6). Although they do not affect the strength of the rock, some people consider them unsightly. *Schlieren* are streaks of differing color, commonly darker or lighter than the rest of the granite. They also mar the uniform appearance of dimension stone. There are few minerals in granite that are deleterious. Pyrite in very small crystals may be susceptible to alteration with the formation of rust spots. Biotite and hornblende may be partially decomposed before the granite is quarried and subsequently weather out in the dimension stone. If these minerals are in fresh condition as the rock comes from the quarry, alteration is negligible for the expected life of a structure. Along the joints in the quarries, percolating ground water frequently causes a selvage of

alteration, called *sap,* commonly discolored by limonite staining. This must be removed, of course, before the stone can be utilized for dimension purposes. The presence of many small dikes in a quarry generally renders the stone useless for dimension stone.

Granite breaks down mechanically into arkosic sand which is composed of the same minerals as are present in the granite, i.e.,

FIG. 4-6. Knots in granite on Mount Waldo, Frankfort, Maine.

quartz and feldspar with the accessory minerals. Usually chemical decomposition accompanies the mechanical breakdown at least to the extent of partially kaolinizing the feldspars, and in part altering the ferromagnesian minerals. Above the timber line in mountain regions, block disintegration is common; and it is frequently difficult to find outcrops of the bedrock in place because of the numerous loose blocks. In the warmer climates, chemical decomposition of the granites kaolinizes the feldspars and alters the biotite and hornblende with production of kaolin and liberation of iron oxides which stain the soil reddish-brown. The quartz remains unchanged. In some of the warmer more humid regions, particularly lowland

areas where the products of alteration are not removed, the residual soil so developed may be of considerable thickness. Residual boulders of weathering are locally developed that very much resemble glacial erratics (Fig. 4-7). In these places the weathering has proceeded most rapidly along the joints. The coarse textured granites weather somewhat more rapidly than do those of finer texture, and in general the fine textured granites are more desirable for dimension stone.

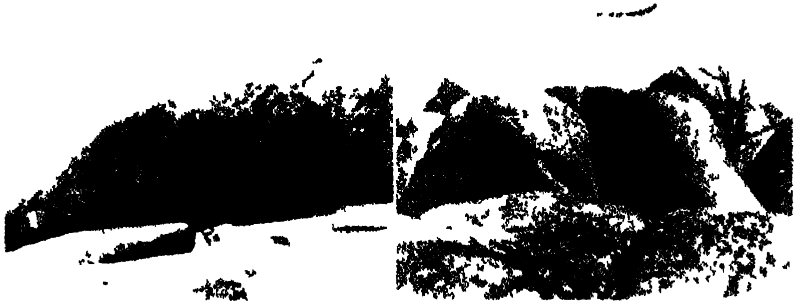


FIG 4 7 Residual boulders in Southeastern Missouri These boulders are formed in place by weathering along joint planes in the granite (W. A. Tarr by courtesy of Mrs W A Tarr)

Commonly associated with granites and related to them are pegmatites, which are coarse and irregular textured igneous rocks composed dominantly of quartz and potash feldspar, and frequently also with plagioclase. Although *pegmatite* is a textural term, because the great bulk of pegmatites are of granitic composition granitic pegmatite is understood, unless the use of the term is qualified. Biotite and muscovite are common accessories in the simple pegmatites, and black tourmaline is not unusual. In the more complex pegmatites, a great variety of minerals may be present; and concentrations of compounds of some of the rare elements, such as beryllium, lithium, boron, fluorine and others, may be found. The pegmatites occur as irregular masses, as dikes, and as sills in a great range of sizes. Fig. 4-8 shows a typical occurrence of pegmatite sills with pinch and swell structure. In many areas *lit-par-lit* injection of pegmatite stringers, veins, and sills converts schists into gneisses or

migmatites. Many of the larger bodies of pegmatites are worked for feldspar, if feldspar masses large enough and clear enough are present to permit the operation. Muscovite mica may make up a considerable portion of some pegmatite masses and some pegmatites are worked for mica. Locally, gem bearing zones are encountered, as shown in Fig. 4-9. The semi-precious stones, tourmaline, aquamarine, and topaz, occur as pocket or cavity minerals in pegmatites.

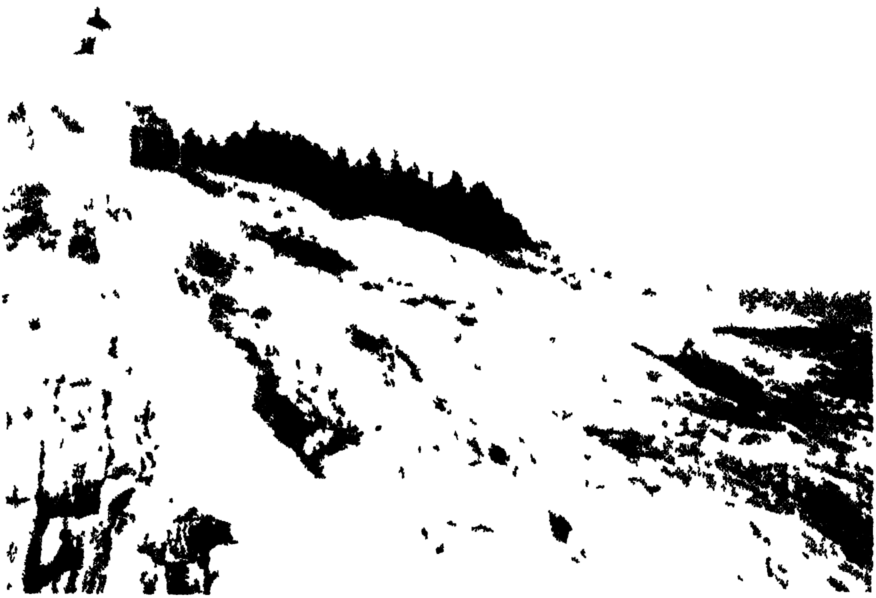


FIG. 4-8. Pegmatite sills with pinch and swell structure, Pemaquid Light, Maine.

The coarse and irregular texture of the pegmatites appears to be due to the large content of mineralizers, notably water, fluorine, and boron. Many pegmatites at least, are late products of the crystallization of a granite mass. An interesting and peculiar textural variety known as *graphic* granite is not uncommonly found in the pegmatites. Skeleton quartz crystals intergrown with feldspar give the rock the appearance of carrying Runic writing. Whether this graphic structure is a result of replacement or simultaneous crystal-

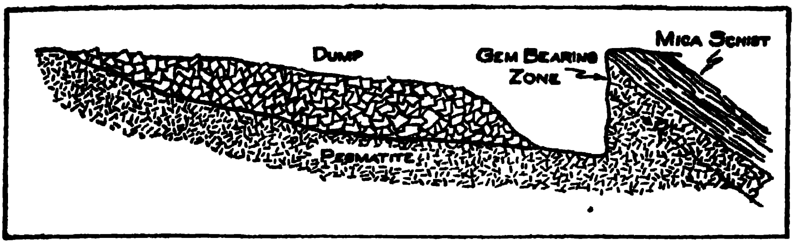



Fig. 4-9. Gem bearing zone in pegmatite. (Maine Geological Survey)

lization of the quartz and feldspar is uncertain. Fig. 4-10 illustrates a polished specimen of graphic granite.

*Syenite.* Syenites are grained igneous rocks composed essentially of potassium feldspar. Biotite and hornblende are commonly occurring accessories. The average syenite has from 80 to 85 per cent feldspar. Quartz, however, is lacking or present only in small percentages. Syenites are not as widely distributed as the granites. Their common geological occurrence is in association with granites. They form marginal facies about granite intrusions and occur less commonly as dikes and irregular bodies. Stocks and laccoliths have

Fig. 4-10. Graphic granite.

also been described. The general properties of syenites are similar to those of granite. Because of the rarity of syenite, it is of little commercial use as structural material, and scant data on its physical properties are available. At Little Rock, Arkansas, a nepheline syenite has been quarried for a number of years. This syenite has a compressive strength of 17,800 pounds per square inch, an absorption of 0.89, a porosity of 3.84, and a weight of 157 pounds per cubic foot.

*Diorite.* Diorites are grained igneous rocks composed dominantly of sodic plagioclase feldspar with either hornblende or biotite as the chief dark constituent. Commonly feldspars make up more than 50 per cent of the rock. If quartz is present, the rock is termed *tonalite* or *quartz diorite.* Diorites occur as marginal facies about granitic intrusions and also form large intrusive masses, as well as occurring as dikes and sills. It is a more abundant rock type than the syenites but less abundant than the granites. With change to a more calcic plagioclase feldspar and an increase of ferro-magnesian mineral, so that the rock is more dark than light, the diorites pass into gabbros. The tendency is to call the rock a diorite, however, on the recognition of hornblende, even if it makes up more than 50 per cent of the rock, because of the common association of hornblende with sodic plagioclase, the feldspar that characterizes the diorites. Diorites have been used more for crushed stone and for monumental and decorative purposes than for structural purposes. Data are not available on their physical properties as building stone. They are more difficult to quarry than the granites because of the common lack of favorable joint systems.

*Gabbro.* Gabbros are grained igneous rocks composed of calcic plagioclase feldspar and typically with augite as the dark accessory mineral. Ordinarily, the augite makes up more than 50 per cent of the rock. Biotite is not common in gabbros. Olivine, however, is not uncommon. A special variety of this rock, having little pyroxene present, is the almost pure plagioclase feldspar rock called *anorthosite.* Gabbros are less abundant probably than the diorites. They underlie large areas locally, however, as in the Adirondacks; and a large intrusion of gabbro is found in the vicinity of Duluth, Minnesota. They are known at many other localities. Gabbros, like di-

orites, have been more widely used as ornamental stone than for construction purposes. Few tests are available which indicate a range in compressive strength from 13,800 to 53,800 pounds per square inch. The absorption in these few specimens was less than 0.3 per cent in all tests. The weight varies from 180 to 190 lbs per cubic foot.

Gabbros and diorites frequently are confused. Three methods of distinction of these rocks in hand specimens may be used: (1) If the dark mineral is determined as hornblende, the rock probably should be called a diorite even if the dark mineral makes up somewhat over 50 per cent of the rock. (2) If primary biotite is present, the rock probably should be called a diorite, since this mineral is much less common in the gabbros than in the diorites (3) If the distinction between hornblende and augite cannot be made, color may be used. Thus if the rock is 50 per cent or more dark minerals, it would be called a *gabbro.*

*Dolerite.* The term *dolerite* is used in this text as applying to intermediate and dark rocks of fine texture, which because of the fineness of grain cannot be distinguished as either *gabbro* or *diorite.* The rock type occurs as marginal facies to basic intrusions, as dikes and sills, and also as an extrusive rock. It is not used as building stone but has been used with success as crushed rock. Its toughness and good abrasion resistance make it suitable rock for this purpose.

*Peridotite.* The gabbros, by a decrease of plagioclase feldspar, pass into a variety made up largely of dark minerals called *peridotite.* The dark minerals constituting this rock type are commonly pyroxenes. Hornblende and olivine varieties are also known. A special variety of peridotite, kimberlite, is of interest because it is a rock in which diamonds are found.

## The Extrusives

The extrusive igneous rocks are those that have been brought to the earth's surface by the forces of volcanism. At the present time most of the volcanic material is emitted from the chimney-like openings of volcanoes. In the past, however, a great deal of lava has been extruded along rents or cracks in the earth's crust. This extrusive action may be classified as fissure or central vent in type.

***Fissure Eruptions.*** Good examples of the fissure types of eruption are found in the northwestern part of the United States, in the Columbia Plateaus of Washington, Oregon, and southern Idaho. In the main, this region is built up of lava sheets which have buried the pre-existing topography completely and cover an area of more than 200,000 square miles. Locally the lava flows reach a composite thickness of over 5000 feet. The Deccan lava plateaus of India are

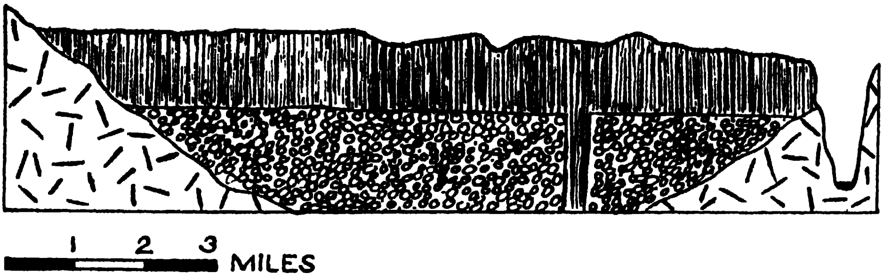



FIG. 4-11. Cross-section of a fissure eruption in Williams Canyon, Arizona Vertical exaggeration × 5. (After W. T. Lee, U. S. Geological Survey)

of similar origin and extent. Minor flows of this type have occurred within historic time in Iceland. One of the best known of these Iceland fissure eruptions took place in 1783. The flows occurred along a fissure 90 kilometers in length. Most of the lavas that have welled out of fissures have been of the basic or dark-colored type. Occasionally associated with fissure lava flows are beds of fragmental rock material caused by the explosive action of the eruption. Fragmental beds are, however, rare in connection with volcanic eruptions of the fissure type. The lavas for the most part were readily mobile and flowed over very low slopes. Individual flows are seldom over a few meters in thickness; the average is perhaps less than 15 meters. Where the fissure eruptions have taken place in valleys, however, the thickness may be somewhat greater. Fig. 4-11 shows a section of a fissure eruption in Arizona.

***Central Vent Eruptions.*** Lavas and other volcanic products have found their way to the surface through chimney-like openings from the earliest times down to the present. At the present time, there are two great belts of volcanoes that are either active at present or have been active in the recent geologic past. The first of these great belts of modern volcanic activity encircles the Pacific Ocean basin. From Tierra del Fuego into Mexico occur many active volcanoes. From Mexico to Alaska, with the exception of Mount Lassen, the volcanoes are either extinct or dormant. From Alaska down the Asiatic coast, through the Philippines to New Zealand, are many active volcanoes. The second major belt extends with a general easterly trend through the Mediterranean Area into Asia Minor. Other lesser belts of volcanic activity are the North-South Atlantic zone which extends southerly from Iceland and includes numerous islands off the west coast of Africa, and the African Rift Valley zone. About 400 active volcanoes are known at present, a good many inactive or dormant volcanoes, and many that are extinct.

Associated Press dispatches from *The New York Times* concerning the disastrous eruption of Mount Etna in 1928 follow:

Rome, November 6, 1928—Mount Etna today appears to have sealed the fate of Mascali and other towns on the eastern coast of Sicily, pushed forward slowly but inexorably by millions of tons of liquid lava vomited by the eruptive craters high up near the volcano's summit, a great fiery river looking like a gigantic slab of white-hot steel has reached the outskirts of Mascali.

Nothing but a miracle can save it now. It is expected that within a few hours nothing will be left of Mascali, a small but flourishing town of about 10,000 inhabitants.

To make the situation even worse the other stream of lava that stopped yesterday, after swallowing up the first few houses of Santalfio, began moving seaward again today. This renders the destruction of Santalfio almost certain and carries Mount Etna's threat to the very doors of the most important town of Giarre.

Rome, November 8, 1928.—Where Mascali yesterday stood as a kind of bulwark against the lava advancing down Mount Etna's sides, there is today a molten waste. Only a few heaps of charred wreckage floating on a river of fuming, semi-liquid volcanic matter mark the spot where

a town of 10,000 people flourished. That, and, higher up on the slope to the left, the cemetery, untouched, its marble tombstones showing white through the cinderladen air as though mourning the death that has overtaken its town.—

***Types of Volcanic Eruption.*** There are two types of volcanic eruption which can be distinguished but which grade into each other—the quiet and the explosive. The thinner and more fluid the lava, the less is there likelihood of violent and explosive eruption. Volcanoes emitting basic, or dark-colored, lavas are in general of the quiet type, whereas those emitting the lighter colored, more acidic lavas, which tend to be more stiff and viscous, are commonly of the explosive type. This difference between the explosive and the quiet type is somewhat analogous to the escape of steam from cornmeal mush. When the cornmeal is added to the boiling water, the mixture is thin and watery, and the steam escapes easily. As the cornmeal swells and the mixture becomes more viscous, the steam escapes violently and little craters of the mush are formed. Volcanic cones built up of quietly eruptive basic lava tend to be broad with relatively gentle slopes, as for example those of the Hawaiian Islands. On the other hand, cones built up about the explosive type of volcano are made of interstratified fragmental material and lava flows and have consequently much steeper slopes.

***The Products of Volcanoes.*** Three types of material are expelled from volcanic vents: (1) gases, (2) solid matter, and (3) lava. The principal gases are water vapor, carbon monoxide and carbon dioxide, sulphur dioxide, hydrogen sulphide, and hydrochloric acid.

The solid materials emitted include the rock fragments thrown into the air by explosive eruption. According to the size of the material, a variety of names are given. Volcanic dust includes the finest material ejected, some of which remains suspended in the atmosphere for months before settling to the earth. Tuffs include materials less than a quarter inch in diameter. Dust and volcanic tuff are the result of violent explosive eruption. When consolidated, the rock is termed volcanic *tuff*. Tuffs are frequently very porous, weak structurally, and susceptible to chemical alteration. The next

coarser grade of material from a quarter of an inch up to several inches in diameter is called volcanic *cinders* Pea sized material frequently is called *lapilli.* More or less globular shaped fragments varying in size from a few inches to a few feet, are called volcanic *bombs* These are masses of lava that have partially or completely solidified in the air. If the ejected material is blown full of holes by the expansion of the contained gases, pumice is formed—a sort of rock froth light enough to float A Japanese eruption a few years ago threw so much pumice out over the ocean, according to report, that it was possible to walk miles over the water on the floating debris Large angular fragments of consolidated lava also are hurled into the air during the shattering of a volcano in violent explosive eruptions

The third form of material extruded by volcanoes is liquid lava which pours forth as molten rock If on hardening the surface is smooth and ropy appearing, it is called *pahoehoe* If the lava continues to flow after the surface has crusted a rough clinkery mass results called *aa* Lavas erupted from volcanoes vary in chemical composition and temperature, and hence also in fluidity Some flows may travel for 20 or 30 miles before solidifying while others harden as soon as they leave the crater It has already been pointed out that the more basic lavas, that is those of darker color, tend to be more fluid, whereas the lighter colored acid lavas are more viscous Consequently pumice is found much more abundantly about the acid type of volcano than it is in association with the basic lavas Many basalts, however, are very porous or cavernous because of the leavening effect of gases. This type of vesicular basic lava is called *scoria*

***Uses of Volcanic Rocks.*** None of the volcanic rocks is used much as dimension stone. Diabase has been used occasionally for monumental and paving block purposes It has good strength and takes a high polish. It is, however, difficult to quarry in large blocks and difficult to work and as a result is but little used The dolerites and basalts when not vesicular or scoriaceous make excellent road metal and are used widely in the construction field as crushed stone This rock variety is commonly known as *trap* The term *trap*, however,

has no geological significance and has been applied indiscriminately to several fine textured, dark-colored rock types by the users of crushed stone. Many of the felsites are valuable as crushed rock also. Both felsites and basalts are wear-resistant and tough. Pumice and cellular or scoriaceous basalts are finding increasing use in the manu-

Fig. 4-12. Columnar structure in lava in Yellowstone National Park (Irwin Douglas)

facture of lightweight building blocks. Because of their cellular nature, these lightweight blocks have excellent insulating qualities against heat, cold, and sound. A well-made block is strong, fireproof, moisture-proof, and at least 40 to 50 per cent lighter than a sand concrete block.

***Structural Features of Volcanic Rocks.*** Slight variations in the composition of lavas may give rise during the flow of the lava to

streaks or laminations somewhat resembling bedding planes in sediments. This flow structure is commonly crumpled, irregular, and wavy in outline; and the individual flow layers are discontinuous. The presence of gas bubble holes has already been noted in the preceding paragraph on classification.

Where the vesicles of scoriaceous lava have been filled with mineral matter deposited by waters which circulate through the openings after the consolidation of the lava, the rock is called an *amygdaloid.* Amygdular fillings may be distinguished from phenocrysts by their irregular or rounded shapes, and sometimes by their mineral composition. The common amygdular fillings are quartz, calcite, chlorite, epidote, and a few other less common minerals. Phenocrysts are chiefly the common igneous rock-making minerals such as quartz, feldspar, hornblende, biotite, augite, and olivine. Occasionally on cooling, a regular pattern of joints is formed called *columnar* structure, as shown in Fig. 4-12. More commonly the cracks are less regular. Most volcanic flows, particularly those of the acid type, show a great abundance of joints, which are closely spaced and cause the rock to break into many small angular fragments.

## Phenomena Associated with Volcanism

In some regions of current or recently past volcanic activity are found phenomena related to the volcanism. Belonging to this group are the widely known fumaroles, hot springs, and geysers. In the course of consolidation either at the surface or not far beneath the surface, gaseous emanations may be given off. These gas vents are called *fumaroles.* One of the most famous areas of fumaroles in the world is the Valley of Ten Thousand Smokes in Alaska, which has been set aside as a national monument. This group of fumaroles was brought into existence by the eruption of Mount Katmai in 1912. This valley, with an area of about 50 square miles, contains thousands of vents from which steam and gases escape. The temperatures of the gases vary from that of ordinary steam to super heated steam so hot that it comes forth as a dry gas.

Also associated with volcanic activity of current or recent date

are *hot springs* Surface waters which penetrate the ground may be heated either by contact with rocks not yet cooled or by gaseous emanations from the volcanic rocks and, re-emerging at the surface, give rise to hot springs Under special conditions the hot springs may be intermittently eruptive. These intermittently eruptive hot springs are called *geysers* One of the best known geyser and hot spring areas in the world is Yellowstone National Park in Wyoming Within this area of about 30 square miles, there are about 100

Fig 4 13 Hot spring terraces in Yellowstone National Park (Irwin Douglas)

geysers and 3000 ordinary hot springs. The temperature of the water in the hot springs varies from lukewarm to boiling. Associated with these hot springs and geysers are frequently found deposits of mineral matter precipitated by the waters on their emergence and cooling at the surface. Calcium carbonate and silica are the most common materials thus deposited. Fig. 4-13 shows terraces built up around one of the Yellowstone hot springs. Because of their eruption geysers are spectacular and have attracted thousands of visitors. Some geysers erupt a water column to a height of more than 200

feet. More commonly, however, the eruption reaches lesser heights and some spout water only to a height of a few feet (Fig. 4-14). One of the most famous geysers in the world is Old Faithful in the Yellowstone National Park which now erupts at intervals of about 66 minutes. The water column is thrown to a height of approximately 160 feet and during each eruption emits 10,000 to 12,000 gallons of

FIG. 4-14 The Thermos Bottle Geyser, Yellowstone National Park (Irwin Douglas)

water. In addition to the Yellowstone, Iceland and New Zealand have large geyser areas.

It is well known that the boiling point of water is raised by increasing pressure. Thus in a tube of water, the boiling point is higher at the bottom than it is at the top. Consequently, if the water at the bottom of a natural tube is heated as by contact with hot rocks or volcanic emanations, circulation will be set up and a hot spring may result. If there are irregularities or constrictions in the tube such that convection is inhibited, the water below the con-

striction may reach the boiling point and enough steam may be generated to lift the column of water in the tube above and cause some outflow at the surface. This reduces the pressure, and the water in the lower part of the system may flash into steam and cause a violent eruption. These conditions are shown in Fig. 4-15, from Day and Allen.

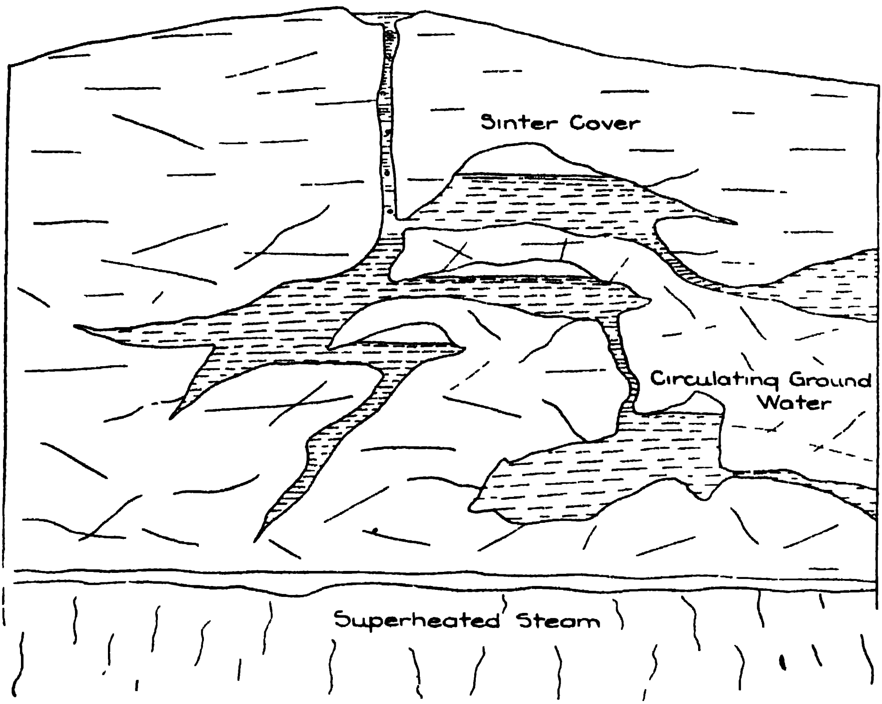



FIG. 4-15. Origin of geysers. (After Day and Allen, courtesy of The Carnegie Institution of Washington)

The fumarole field of Tuscany north of Rome has been utilized as a source of power, and in recent times four central power houses have been built capable of generating 25,000 horsepower each. The electric power generated is transmitted to several cities for distances of 50 to 60 miles. Wells have been driven to a depth of more than 600 feet, increasing both the temperature and flow of the steam. There is a by-product of several gases, the most important of which

are carbon dioxide, used as a refrigerant, and helium. Ammonium carbonate, boric acid, and sodium carbonate are also recovered.

In California 75 miles north of San Francisco, eight wells have been driven in a small fumarole field. Four of the wells are estimated to be able to deliver 1300 horsepower each. Similar explorations have been made in Java, although to date no record of the actual installation of power plants drawing on this source has come to attention. In Reykjavik, Iceland, a municipal hot water supply is drawn from the near by hot springs In the future, possibly, more use of this energy source may be made in favorably situated regions

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CHAPTER V

# ROCK WEATHERING AND THE REGOLITH

ROCKS AT OR CLOSE TO THE SURFACE OF THE EARTH ARE subject to disintegration and decay. The disaggregated products accumulate as "soil." The processes involved in rock destruction and the properties of the resultant materials merit careful study by civil engineers, for with this class of material many engineering problems arise.

It is at once apparent that the engineer who deals with unconsolidated materials as fills or foundations or as structural materials for base courses, surfacing, or masonry, or for utilization in sanitary engineering, or in other special ways, is inadequately trained, technically, unless he is familiar with the geological principles involved. Heterogeneity rather than homogeneity is characteristic of many parts of the regolith. Both lateral and vertical variations in mechanical make-up, lithologic content, and structure are common. The close student of geological phenomena is in position to appreciate, anticipate, and even to take advantage of the heterogeneity where it exists, or to overcome difficulties imposed by it. The modern development of soils mechanics is the result of attempts by engineers to measure quantitatively the properties of the regolith imposed by the geologic processes which have formed it and acted upon it, and to apply the measurements to engineering practice. In the fields of civil and agricultural engineering especially, soil studies are of high economic importance.

At most places on the earth's surface there exists a greater or lesser

thickness of unconsolidated rock, the top zone of which supports organic growths. Only locally is this cover lacking, and surface exposures of ledge are limited. These unconsolidated or semiconsolidated materials constitute what is termed the *regolith,* or *mantle rock.* The regolith may be hundreds of feet thick, or it may be wanting entirely. The upper portions of the regolith, in which organic substances are incorporated, and which is more or less modified biologically, is the *soil.* Engineers extend the term *soil* to include all regolith material.

The regolith consists of two major groups of materials: (1) residual or sedentary materials, developed *in situ* by the mechanical and chemical processes of rock alteration and accumulation of certain types of materials, and (2) transported materials, which have been removed from their place of origin and redeposited by one of the several geological agents. A classification of the regolith, based on these two major subdivisions, is shown in Table 5.1.

TABLE 5.1. CLASSIFICATION OF THE REGOLITH *

| | | |
|---|---|---|
| Sedentary | Residual deposits | Residuary gravels, sands and clays, laterite, etc. |
| | Cumulose deposits | Peat, muck, and swamp soils, in part |
| | | Marls, organic oozes, coquina, in part |
| | | Chemical precipitates as salt, etc. |
| Transported | Gravity deposits | Talus and cliff debris, material of avalanches, earth flow and earth creep |
| | Alluvial deposits | Modern alluvium, marsh and swamp deposits, in part |
| | Eolian deposits | Wind-blown material, sand dunes, and loess, volcanic dust, etc. |
| | Glacial deposits | Till and stratified drift |
| | Lacustrine and Marine deposits | Beach and bottom deposits |

* Modified after Merrill.

As shown in Table 5.1, sediments can be classified on a genetic basis according to the agent of deposition: for example, *eolian,* or wind-blown deposits; *fluviatile*, stream-borne sediments; *marine,* sea deposits; or *glacial,* deposits left by ice. In the field, the geologist attempts to infer the origin of the sediments which he encounters. In this attempt he is often successful. Frequently, however, the conditions of deposition are debatable; and there are several other schemes of classification that can be used.

***Mechanical Analyses.*** The separation of the various grade sizes composing a sample of the regolith is one of the first steps in the

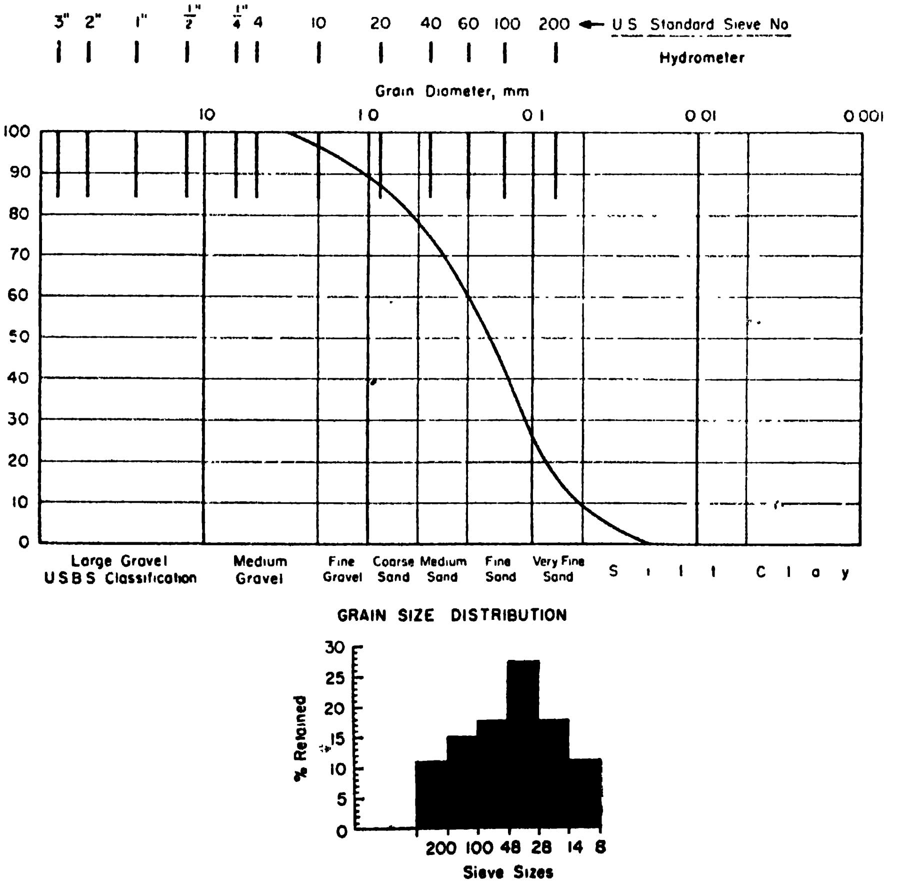


FIG. 5-1. Cumulative graph of mechanical analysis above, with histogram representation, below.

laboratory studies The most widely used methods of mechanical analysis are screening and hydrometer analysis The results of mechanical analyses are shown graphically in several ways Histograms (Fig 5 1) show the composition effectively More useful to the engineer, however, are the cumulative graphs Fig 5-1, a cumulative curve, shows this means of presenting mechanical analysis data

Geologists commonly classify regolith materials according to texture, the same practice followed by engineers The U S Bureau of Public Roads and many engineering laboratories classify the clastic sediments as *gravel, sand, silt*, and *clay*, according to dimensions

| | |
|---|---|
| Gravel | Greater than 2 mm |
| Sand | 2 mm–0 05 mm |
| Silt | 0 05–0 005 mm |
| Clay | Less than 0 005 mm |

Various grade sizes occur mixed in the sediments In unconsolidated sediments the mixtures give rise to various soil terms such as *silty clay clay loam, loam*, and the like The U S Bureau of Reclamation classification of soils is the basis of Table 5 2 an alternative classification in graphic form is shown in Fig 5 2

Various attempts have been made to classify soils into groups according to engineering properties None of the classifications has been entirely satisfactory although several have been widely used The countless possible variations in soils and their properties make classification schemes based on engineering properties of somewhat limited value Diverse soil types may have similar responses to a given stress condition or conversely, similar soil types may react quite differently under similar stress conditions Further, soils which react similarly under certain conditions may differ markedly in their response to other conditions *Each individual engineering problem relating to the regolith demands individual analysis, based on studies of the particular material involved* The classification presented in Table 5 3, in summary and abbreviated form, is one used by many civil engineers, and in connection with Table 5 2, the Bureau of Reclamation classification of soils types, is of interest The table is self-

## TABLE 5.2 SOIL TYPES—IDENTIFICATION AND DESCRIPTION[a]

### Coarse-Grained Soils[b]

| TYPE | FIELD IDENTIFICATION[c] | GROUP SYMBOL[d] | TYPICAL NAMES |
|---|---|---|---|
| *Gravels*[e] | | | |
| Clean gravels (little or no fines) | Wide range in grain size and substantial amounts of all intermediate particle sizes | GW | Well-graded gravels, gravel-sand mixtures, little or no fines |
| | Predominantly one size or a range of sizes with some intermediate sizes missing | GP | Poorly graded gravels, gravel-sand mixtures, little or no fines |
| Gravels with fines (appreciable amount of fines) | Non-plastic fines (for identification procedures see ML below) | GM | Silty gravels, poorly graded gravel-sand-silt mixtures |
| | Plastic fines (for identification procedures see CL below) | GC | Clayey gravels, poorly graded gravel-sand-clay mixtures |
| *Sands*[b] | | | |
| Clean sands (little or no fines) | Wide range in grain sizes and substantial amounts of all intermediate particle sizes | SW | Well-graded sands, gravelly sands, little or no fines |
| | Predominantly one size or a range of sizes with some intermediate sizes missing | SP | Poorly graded sands, gravelly sands; little or no fines |
| Sands with fines (appreciable amount of fines) | Non-plastic fines (for identification procedures see ML below) | SM | Silty sands, poorly graded sand-silt mixtures |
| | Plastic fines (for identification procedures see CL below) | SC | Clayey sands, poorly graded sand-clay mixtures |

*Information required for describing soils:* Give typical name; indicate approximate percentages of sand and gravel; maximum size; angularity, surface condition, and hardness of the coarse grains; local or geoloic name and other pertinent descriptive information; and symbol in parentheses. For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics.

*Example:* Silty sand, gravelly; about 20% hard, angular gravel particles ½-in. maximum size; rounded and subangular sand grains coarse to fine; about 15% non-plastic fines with low dry strength; well compacted and moist in place; alluvial sand; (SM).

## Fine-Grained Soils[g]

| TYPE | IDENTIFICATION PROCEDURES[h] | | | GROUP SYMBOLS | TYPICAL NAMES |
|---|---|---|---|---|---|
| *Silts and Clays* | Dry Strength (Crushing Characteristics) | Dilatancy (Reaction to Shaking) | Toughness (Consistency Near Plastic Limit) | | |
| Liquid limit less than 50 | None to slight | Quick to slow | None | ML | Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity |
| | Medium to high | None to very slow | Medium | CL | Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays |
| | Slight to medium | Slow | Slight | OL | Organic silts and organic silt clays of low plasticity |
| Liquid limit greater than 50 | Slight to medium | Slow to none | Slight to medium | MH | Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts |
| | High to very high | None | High | CH | Inorganic clays of high plasticity, fat clays |
| | Medium to high | None to very slow | Slight to medium | OH | Organic clays of medium to high plasticity |
| *Highly organic soils* | Readily identified by color, odor, spongy feel, and frequently fibrous texture | | | Pt | Peat and other highly organic soils |
| | *Information required:* Give typical name, indicate degree and character of plasticity, amount and maximum size of coarse grains, color in wet condition, odor if any, local or geologic name and other pertinent descriptive information, and symbol in parentheses. For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture, and drainage conditions. *Example:* Clayey silt, brown; slightly plastic, small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (ML). | | | | |

[a] After a chart prepared by the U. S. Bureau of Reclamation.

[b] More than half the material is larger than No. 200 U. S. Standard sieve size. A particle of the No. 200 sieve size is about the smallest visible to the naked eye.

[c] Excluding particles larger than 3 inches and basing fractions on estimated weights.

[d] *Boundary classifications:* Soils possessing characteristics of two groups are designated by combinations of group symbols. For example, GW–GC = well-graded gravel-sand mixture with clay binder.

[e] More than half of coarse fraction is larger than No. 4 sieve size. For visual classification the 1/4-inch size may be used as equivalent to the No. 4 sieve size.

[f] More than half of coarse fraction is *smaller* than No. 4 sieve size.

[g] More than half of material is *smaller* than No. 200 sieve size.

[h] On fraction smaller than No. 40 sieve size.

TABLE 5.3 TABULAR SUMMARY OF CHARACTERISTICS OF SUBGRADE SOILS*

| Group | General Type | Grading | | | | Remarks |
|---|---|---|---|---|---|---|
| | | % Sand | % Silt | % Clay | Characteristic | |
| A-1 | Sand, sandy loam | 70 – 85 | 10 – 20 | 5 – 10 | Uniform | High internal friction, good binder, high cohesion, stable wheel-loads in all moisture states. |
| A-2 | Sand, clay loam, sandy clay, sandy loam | 55 + | Low | High | Lacks certain sizes | High internal friction and high cohesion, if properly graded. Softens when wet, dusty in drought. |
| A-3 | Sand, gravel | 50 – 95 | 0 – 5 | 0 – 10 | Coarse | High internal friction, no cohesion; poor surface good base. Not subject to frost heave. |
| A-4 | Silty loam, silty clay loam, clay loam, loam | – 55 | 30 – 90 | 10 – 30 | Lacks coarse and fine sizes | Variable internal friction; slight cohesion, high capillarity, water absorption causes instability; subject to frost heave. |
| A-5 | | | Like A-4 | | | Like A-4 but elastic; difficult to compact. |
| A-6 | Silty clay, clay | Low | Medium | 30 + | Lacks coarse and intermediate sizes | High cohesion, absorbs water when disturbed, and becomes soft, subject to flow and slide. Low internal friction. |
| A-7 | | | Like A-6 | | | Like A-6 but elastic. |
| A-8 | Peat and muck | | | | High organic content | Unstable. |

* Modified from Winterkorn The classification into the eight groups is based on performance, and upon the determination of certain physical properties such as plastic index, liquid limit, and shrinkage.

explanatory. Soils assigned to the A-1, A-2, and A-3 groups, with high internal friction, generally are satisfactory foundation materials; soils of the A-4 and A-5 groups are variable but generally suspect; soils of the A-5, A-6 groups are commonly unsatisfactory; and the organic soils, of A-8 classification, are generally unstable.

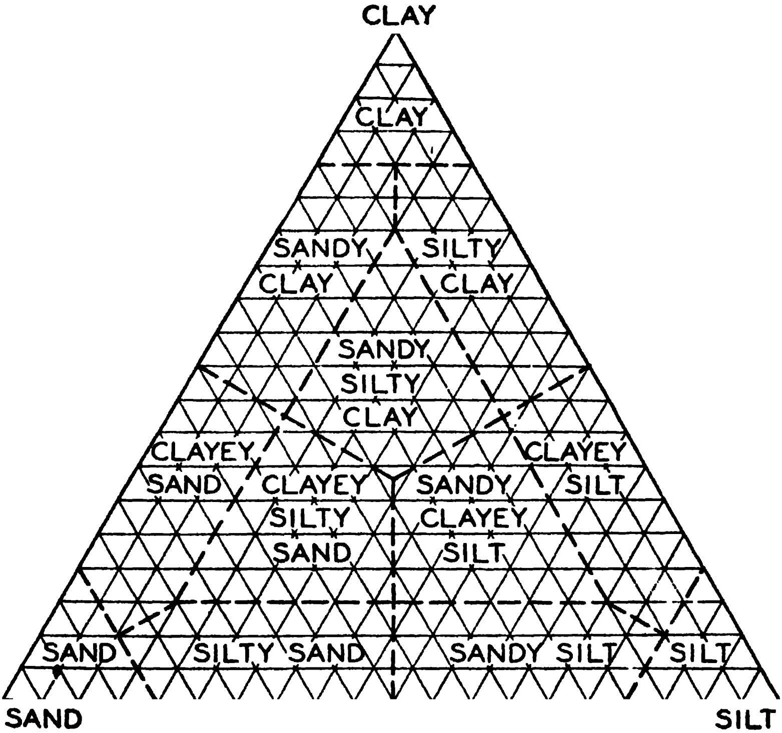


FIG. 5-2. Soil classification triangle.

***The Soil Profile.*** Another method of classification is based on the soil profile. The regolith, whether sedentary or transported, under favorable conditions supports a greater or lesser amount of vegetation and displays characteristically a series of more or less readily recognized zones or "horizons". This sequence of layers or zones is termed the *soil profile.* Three distinct zones are recognizable as shown in Fig. 5-3. The *A* horizon is the zone in which organic life is most abundant, including many microscopic organisms; and this is, of

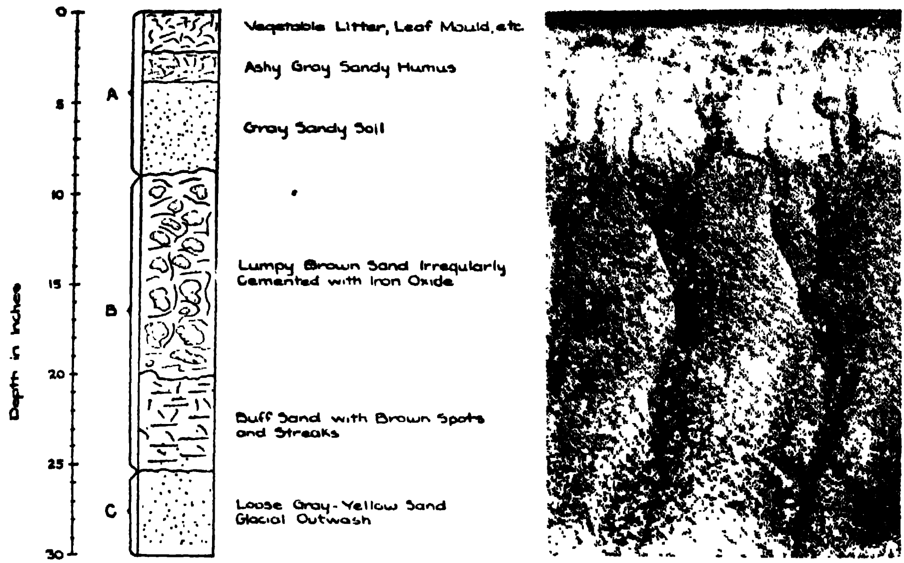


FIG. 5-3. The soil profile.

course, the zone of tillage. It is, characteristically, in the humid regions, the zone of leaching and eluviation—eluviation being the washing out of the finer soil particles. The *B* horizon, or zone of accumulation, is the zone enriched by materials derived from the overlying *A* zone. The *C* horizon is the parent regolith material. It is obvious that conditions of weathering, namely, climate, ground water conditions, slope, vegetation, and other organic factors, as well as the nature of the regolith material from which the soil has been formed are important in determining the character of the soil profile. Indeed, at many places, because of the recency of deposition, the character of the processes acting upon the regolith, or the kind of material composing the regolith, the typical zoning into *A*, *B*, and *C* horizons is ill-defined or absent. Locally, also, rapid removal of the soil inhibits the development of the normal profile.

## THE WEATHERING PROCESSES

All rocks at or near the earth's surface are subjected to the processes of weathering. Some resist the attack successfully and are

quite stable under surface or near-surface conditions. Others undergo profound alterations. Two types of change are included under the general head of weathering. These are (1) physical or mechanical changes and (2) chemical changes. Although from place to place on the earth's surface, the effects of one or the other of the weathering processes may be dominant, they are concomitant processes, occurring simultaneously; mechanical weathering is usually attended by some degree of chemical weathering, and chemical weathering affects to a degree, at least, mechanical breakdown.

***Mechanical Weathering.*** Mechanical weathering is the breakdown of a rock mass into smaller particles without chemical alteration. There are two chief types of this mechanical weathering. The first of these, called *block disintegration*, results from the development of joints which break the rock mass into large numbers of individual blocks or fragments. The second type, called *granular disintegration*, results from loss of cohesion between the individual mineral grains, so that the rock becomes an incoherent granular mass. Granular disintegration is limited to the coarser-grained rocks and affects particularly such rocks as the coarser-textured granites. Block disintegration affects rocks of all textures. It is particularly conspicuous, however, in the finer textured varieties. Besides block and granular disintegration, abrasion and impact mechanically comminute rocks.

*Temperature Effects.* Changes of temperature effect changes in the volume of rock masses. As the outside portion of a rock mass is heated, it expands, and both tensile and shearing stresses are set up between the external and internal portions. Not only do the outside and inside parts change volume differentially, but also the minerals composing a rock have different coefficients of expansion. Furthermore, the coefficient of expansion in most minerals varies according to the crystallographic direction.

There is a difference of opinion as to the range of temperatures necessary to produce rock destruction. Professor Blackwelder[1] con-

[1] Blackwelder, E., "Fire as an Agent in Rock Weathering." *Jour. Geol.*, Vol. 35, 1927, pp. 134-140.

cluded from a series of experiments that most rocks can withstand rapid heating and cooling through a range of 300° C Inasmuch as the maximum daily range of temperature due to insolation is probably not over 75°, he concluded that diurnal changes in temperature were unimportant in rock destruction The observations of many geologists, however, would seem to indicate that normal temperature variations have produced disrupting effects Possibly fatigue plays a part Forest fires have undoubtedly swept over wooded areas from time to time ever since the development of trees, and a considerable amount of rock destruction can locally be attributed to fire Incidentally, fire has been used to cause spalls of dimension block size in quarrying granites in some areas

*Frost Action* When the temperature range is such that alternate freezing and thawing occur, disrupting effects due to the expansive force of water confined in the rock may be effective The absorption of most of the igneous rocks is so low that block rather than granular disintegration commonly results from this process

*Abrasion, Impact, and Crushing* Rocks are broken mechanically also by various processes involving movement, particularly of one rock mass over or against another Ice sheets, for example, have overridden large areas of the earth's crust resulting in the production of broken rock material down to the finest clay sizes In swift flowing streams, both abrasion and impact may cause rock comminution Along the shores of lakes and seas, wave action has produced noteworthy mechanical effects The abrasive action of artificial sand blasts in cleaning up rock structures and finishing dimension stone is familiar to many, the natural sand blast, particularly in the dry regions, produces similar results in nature Typical effects of these agents upon the shapes of pebbles are shown in Fig 5-4 Less important, but locally noteworthy, is the grinding and crushing sometimes developed along dislocations of portions of the earth's crust called *faults*

There are other minor causes contributing to rock disintegration Among these might be mentioned the wedge action of growing roots, the crystallization of minerals within or on the surface of rocks, and

the action of organisms Man himself through his excavations and operations on and within the earth has caused or promoted in the aggregate a great deal of rock breaking

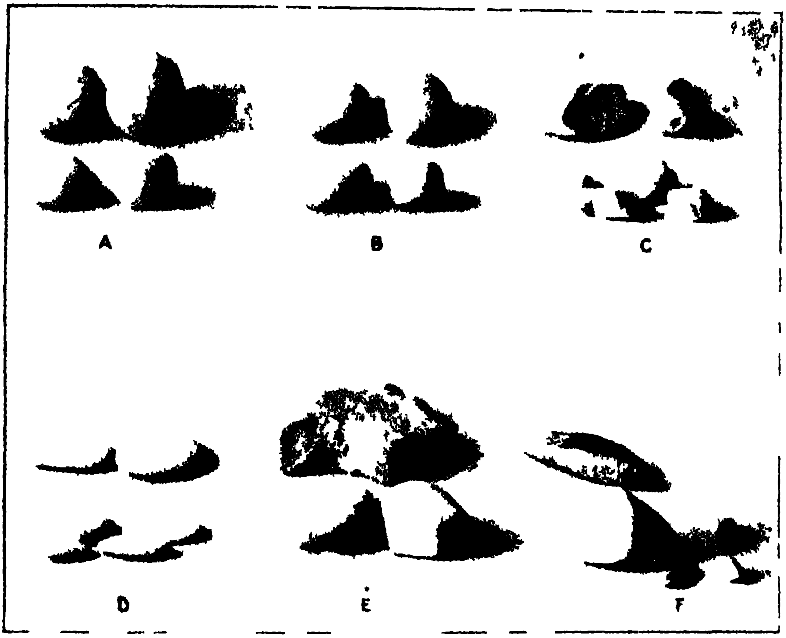


FIG 5 4 Shapes of pebbles of different origins A rounded B subrounded C angular D discoid E faceted and striated glacial pebbles F Dreikanter faceted by wind blown sand About one fourth natural size Courtesy of the McGraw Hill Book Company

*Summary* The conditions that favor mechanical weathering are large temperature ranges aridity, and steep slope The large temperature ranges are found in the higher latitudes and in the desert regions Steep slopes promote mechanical rock destruction by the commonly rapid removal of the broken fragments, thus preventing a blanketing effect of accumulated material The mountainous and the dry regions are also areas of strong wind action, and present-day glaciers are found only in the high latitudes or high altitudes The marked diurnal changes of temperatures in the deserts and the large seasonal range of temperatures in the higher latitudes are well known and need no special comment

***Chemical Weathering.*** Chemical weathering is the alteration of rocks by means of mineralogical or chemical changes induced by surficial agents. The atmosphere consists of nitrogen, oxygen, carbon dioxide, several inert gases, varying amounts of moisture, and, occasionally or locally, acid constituents given off by volcanoes or industries. The active ingredients concerned in rock weathering are oxygen, carbon dioxide, water vapor, and acids. These are dissolved in the moisture which falls as precipitation, and they may be carried into the rock as a certain amount of moisture penetrates the earth's surface. Decaying vegetation and the soil air also contribute organic acids, carbon dioxide, and oxygen to the water which penetrates the ground. The chief processes of chemical weathering then, are *oxidation, hydration, carbonation,* and *solution.* As a result of these, silica is often lost from the silicate minerals, the process of silica abstraction being termed by some *desilication.*

Of the elements known (some 103 in number), eight make up the great bulk of the outer portions of the earth These are in their order of abundance:[2]

| | *Weight Per Cent* |
|---|---|
| Oxygen | 46.60 |
| Silicon | 27 72 |
| Aluminum | 8.13 |
| Iron | 5.00 |
| Calcium | 3.63 |
| Sodium | 2.83 |
| Potassium | 2.59 |
| Magnesium | 2.09 |
| | 98.59 |

Thus, all the other elements, while locally concentrated, make up only 1.41 per cent of the outer portions of the earth. It will be noted in the previous discussion of the rock-making minerals that these eight elements, in various combinations, make up the relatively few minerals which constitute the great bulk of the earth's observable solid portion. Of these elements, oxygen, silicon, and aluminum fre-

[2] Mason, Brian, *Principles of Geochemistry,* Wiley· New York, 1958, p. 46

quently act as a group. Under the influence of chemical weathering, aluminum, silicon, and oxygen jointly tend to take on water, forming one of the stable clay minerals. Potassium, calcium, sodium, and magnesium commonly unite with carbon dioxide and oxygen to form the carbonates which are soluble in the presence of excess carbon dioxide or in the presence of acids Iron takes on oxygen and water, forming stable hydrated iron oxides. It should be fully recognized, however, that other combinations take place, as for example, the formation of iron carbonate or potassium hydroxide.

Chemical reactions can be written for some of the alterations. Because of the complexity of the weathering process, it is not certain that any of the following chemical reactions actually take place in nature; but they nevertheless point out the trend of alteration.

*The Feldspars.* Orthoclase may be transformed under the influence of chemical weathering directly into kaolinite. The reaction may be written:

$$\underset{\text{Orthoclase}}{2\ KAlSi_3O_8} + CO_2 + 2\ H_2O = \underset{\text{Kaolinite}}{H_4Al_2Si_2O_9} + 4\ SiO_2 + K_2CO_3$$

From this equation, it is seen that orthoclase, under the action of carbon dioxide and water, may form kaolinite with the liberation of silica and potassium carbonate. The silica liberated is not to be thought of as quartz, but as soluble or colloidal silica—probably the latter, which may subsequently become quartz on crystallization. It probably often happens, however, that the orthoclase does not change into kaolinite directly but into some intermediate silicate. Plagioclase feldspars alter in much the same way. Albite, or the soda feldspar, for example, may alter into kaolinite. The reaction for this change may be expressed as:

$$\underset{\text{Albite}}{2\ NaAlSi_3O_8} + CO_2 + 2\ H_2O = \underset{\text{Kaolinite}}{H_4Al_2Si_2O_9} + 4\ SiO_2 + Na_2CO_3$$

The change may be to a mica instead of kaolinite. For the lime feldspar, anorthite, a reaction to kaolinite can be written as:

$$\underset{\text{Anorthite}}{CaAl_2Si_2O_8} + CO_2 + 2\ H_2O = \underset{\text{Kaolinite}}{H_4Al_2Si_2O_9} + CaCO_3$$

It has already been noted that the feldspars are the commonest

of all minerals. It should be remarked, also, that the soda and the lime feldspar virtually always occur in nature in combination with each other. Various products of alteration other than those indicated in the preceding equations are possible and frequently occur. Examples of these are epidote, zoisite, and the zeolites. Under certain conditions of extreme weathering, the kaolinite formed is transformed by desilication into the hydrous aluminum oxide, gibbsite, the chief mineral constituent of the aluminum ores.

*The Micas.* Muscovite mica is, in general, stable under conditions of weathering and is common in weathered materials. Biotite, on the other hand, is less stable and commonly alters into chlorite and epidote. The complexity of reactions of this type is illustrated in the following equation showing the transformation of biotite to epidote:

$$6\,\underset{\text{Biotite}}{H_2K_2Mg_4FeAl_4Si_6O_{24}} + 20\,CaCO_3 + 4\,CO_2 + 3\,O =$$

$$2(\underset{\text{Epidote}}{H_5Ca_{10}Al_{12}Fe_3Si_{15}O_{65}}) + 6\,SiO_2 + 18\,MgCo_3 + 6\,K_2CO_3 + H_2O$$

It is somewhat doubtful, however, if the reaction in nature actually follows that just shown for the development of epidote from biotite.

*Amphiboles and Pyroxenes.* Amphiboles and pyroxenes are complex series of minerals, formulae for which are difficult to write. Hornblende, a common amphibole, approximates $NaCa_2(MgFe)_5AlSi_7O_{22}(OH)$, and augite, a common pyroxene, $(Ca,Mg)(Mg,Fe)(Al,Fe)_2\,Si_3O_9$. Both the pyroxenes and the amphiboles are analogous to the plagioclase feldspars in that each constitutes an isomorphous series. Because of the chemical complexity and variability of both augite and hornblende, the common representatives of these groups, no attempt will be made here to write out illustrative chemical reactions. The trend of alteration, however, is well known. Both augite and hornblende alter to epidote and chlorite, chlorite being the more common product of weathering. More complete weathering leads to the formation of kaolinite and the iron oxides, and the carbonation of calcium and magnesium.

*Olivine.* Olivine, a common constituent of the basic igneous

rocks, commonly yields serpentine on weathering. The reaction might be expressed by:

$$\underset{\text{Olivine}}{6\,MgFeSiO_4} + 4\,H_2O + O_2 = \underset{\text{Serpentine}}{2\,H_4Mg_3Si_2O_9} + \underset{\text{Magnetite}}{2\,Fe_3O_4} + 2\,SiO_2$$

***Summary.*** The mineralogical changes that have been indicated are in the direction of simplification, with the tendency to produce as end products of weathering the clay minerals, represented by kaolinite, and the hydrated iron oxides. Quartz remains unchanged, although it may be comminuted in the process of rock destruction. In the alteration of the silicate minerals, it should be noted that the silica is removed either as a colloid or in true solution. It is not removed as quartz. Calcium and magnesium carbonate and silica are taken into solution and may be redeposited either locally or elsewhere. Potassium has an affinity for clay and tends to remain absorbed or adsorbed by the clay particles. Sodium is eliminated in large measure, forming salt deposits or eventually finding its way into the sea. The ferrous iron is largely oxidized to the ferric form and remains in the soil as hydrated ferric oxide. Ordinarily there is little change in the total content of alumina in the rock. Water is almost invariably increased as a result of the weathering processes. Intermediate products of weathering include chlorite, talc, epidote, and a few others.

The conditions which favor chemical weathering are warm, humid climates, vegetation, and gentle slopes. Thus it is that the humid tropics and subtropics of lowland character are the regions that most favor chemical alterations. The badly leached, sterile, red soils (laterites) so widely found in these regions testify to the efficacy of the chemical alterations. It should be emphasized again, however, that the mechanical and chemical processes of rock destruction are complementary and contemporary processes and that in most places at most times the two types of alteration are proceeding simultaneously.

It is interesting to note that the order of susceptibility to the weathering processes shown by the minerals of the igneous rocks is similar to the order of crystallization, or the reaction series as given

on page 40. The basic minerals are the most susceptible to chemical alteration, muscovite and quartz the least susceptible. When all the products of weathering are considered, a large increase of volume is shown. The minerals resulting from the alteration are in general those of lower specific gravity. *The weathering changes are those necessary to bring the rock into harmony with the environment and represent a type of adaptation to environment.*

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CHAPTER VI

# MASS PROPERTIES OF THE REGOLITH

A BLANKET OF UNCONSOLIDATED OR SEMICONSOLIDATED material composed of mixtures of particles of varying sizes of varying mineral and lithologic components, and with varying amounts and kinds of organic substances covers much of the earth's surface. Locally the blanket is thin; locally it is thick; and at some places it is missing entirely, where bare ledge outcrops at the surface. This blanket of "soil" is the *regolith.* The composition, arrangement, and structures of the regolith must be known so far as they influence the engineering properties of bearing loads, drainage characteristics, utility as construction materials—fills or aggregates, or slope stability.

Many engineering structures are founded on or in the regolith. Generalizations as to the bearing strength and other engineering properties may be found in the engineering literature that in some instances are misleading, partial truths, or only locally applicable. The realization of the complexity of soils as engineering materials and of the need for careful investigation in advance of many construction projects has become widespread only within recent years. The development of soils mechanics marks a great stride forward in modern civil engineering. Inasmuch as the regolith is a result of geologic processes, geologists have naturally been concerned with the study and interpretation of it. The early paper by Ladd (1898) and the more recent paper by Mead (1925) are particularly significant in the light of recent developments in the field of soil mechanics.

***Assortment.*** The regolith consists of both sorted and unsorted material. Deposits laid down by water or wind are sorted to varying degrees of perfection. Deposits laid down by ice or formed by earth movements—for example, landslides or mudflows—or by weathering *in situ* generally have a wide range of particle sizes. Some degree of segregation of particle sizes, however, usually results from any movement of rock debris.

A numerical expression, the *sorting coefficient*, $S_0$, is in common use. If sorting is taken as a measure of the dimensional spread of particle sizes of a sediment, the coefficient of sorting is a measure of the average quartile spread where $Q_3 > Q_1$:

$$S_0 = \sqrt{Q_3/Q_1} \quad \text{i.e.,} \quad \sqrt{\frac{\text{max. diameter of smallest 75\% by wt.}}{\text{max. diameter of smallest 25\% by wt.}}}$$

The quartile values are determined by the intersection of the 25 per cent and 75 per cent lines with the cumulative curve (see Fig. 5-1, page 72). A difference in coarseness of samples or of units of measurement is not reflected in this expression. If $S_0 < 2.5$, the sand is well sorted.

Another expression, credited to the distinguished civil engineer Allen Hazen, is the *uniformity coefficient, U.*

$$U = D_{60}/D_{10}$$

where $D_{60}$ is that grain diameter which has 60 per cent by weight of the sample of smaller diameter, and $D_{10}$ is the grain diameter that has 10 per cent by weight of the sample of lesser diameter. These values are readily read from a cumulative curve of grain sizes determined by mechanical analyses, as was shown in Fig. 5-1, page 72.

Inasmuch as the grading or assortment of sizes and their proportions have a profound influence on the amount of mixing water required to produce a workable mixture and also on the amount of cement required to produce a mortar or concrete of specified strength, engineers are directly concerned with the mechanical composition of mineral aggregates. In engineering practice, an empirical factor called the *fineness modulus* is widely used as an index of coarse-

ness or fineness of aggregates. This modulus, F.M., is obtained by taking the sum of the cumulative percentages of material retained on each screen of the series, 6″, 3″, 1½″, ¾″, ⅜″, and Nos. 4, 8, 16, 30, 50 and 100 of the U. S. Standard Screen Series, and dividing the sum by 100.

Although no standard grading can be set for all kinds of mortar or concrete to produce workable mixes of specified strengths, certain requirements of grading for different purposes are set up by the American Society for Testing Materials.* For example concrete sands must be within the limits:

| *Size* | *Per Cent Passing* |
|---|---|
| ⅜″ | 100 |
| No. 4 | 95-100 |
| No. 8 | 80-100 |
| No. 16 | 50-85 |
| No. 30 | 25-50 |
| No. 50 | 10-30 |
| No. 100 | 2-10 |

In the United States over $60,000,000 per year is spent for screening aggregates and recombining into suitable gradings for concrete.

***Particle Shapes:*** The shapes of the particles in the regolith are likewise extremely variable. Some sediments consist predominantly of nearly spherical particles, some of flat or scale-like shapes, and some of very angular particles. The shapes of the fragments are determined by the nature of the parent material, the process of fragmentation, and the agency and extent of transportation. Sediments derived from shales, slates, and schists tend to have flat particles. Sediments derived from the massive rocks, for example quartzites, lavas, or granites, vary from highly angular to nearly spherical, depending on the amount of wear during transportation. Clays consisting largely of the clay minerals, for example kaolinite, are largely made up of tiny scale-like particles, whereas the clays consisting of pulverized rock fragments, for example the glacial clays, may consist largely of very angular fragments. The shapes of

* *American Society for Testing Materials Standards*, A.S.T.M., Baltimore, Md., 1958

the fragments have marked influence on such properties of the material as porosity, permeability, and reaction to load, and also on the amount of water and cement required to produce a concrete of specified workability and strength.

***Mineral Constituents.*** In general the minerals in a residual soil that has been formed *in situ* are minerals of the parent material that are resistant to chemical change. In this category are quartz, zircon, tourmaline, muscovite, and often other minerals in various stages of alteration. New minerals in the residual soil– the iron oxides, manganese oxides, and clay minerals in particular—may predominate. If the soil is transported, the degree of sorting that is imposed on the material depends on the agent of transportation and the environment of deposition.

If the regolith materials are the result of mechanical weathering, the constituent particles are the same mineralogically as the parent material.

At many places, if not at most, the regolith is a mixture of materials that are in part the result of chemical alteration and in part the result of disintegration, for the two processes are complementary.

## TRANSPORTATION AND DEPOSITION OF SEDIMENTS

It has been shown in the preceding discussion that mechanical and chemical weathering break down coherent or solid rocks into fragmental, unconsolidated particles. The products of weathering are subject to transportation by any of the geologic agents capable of removing them. Wind, water, ice, gravity, and, to a lesser extent, organisms are the agents of transportation. The action of these agents is taken up subsequently, and the forms of the deposits which result will not be traced in detail here.

In addition to the solid particles produced by weathering, it has also been shown that chemical weathering commonly liberates soluble substances which remain adsorbed or absorbed in the weathered material or are carried away in solution by circulating waters. If the latter happens, two possibilities are apparent: either the dissolved substances are precipitated or they remain in solution, as for

example the salts of the seas. There are various ways in which precipitation is brought about, and various types of deposits which result. In the present discussion, we are concerned only with deposits which form sedimentary masses.

## Structural Features of Sediments

Sediments have certain structural features that result from their mode of deposition or from processes acting upon them prior to consolidation. These structures of depositional or diagenetic origin are *primary* structures. The primary structures of principal importance are: stratification, lamination, cross-lamination, ripple mark and primary joints.

***Stratification.*** The most common and the most prominent structural characteristic of sediments is layering, called *stratification* or *bedding*. The *beds* or *strata* may differ in grain size, grain arrangement and assortment, color, or mineralogical make-up, or in the combination of these elements.

The fluid agents of transportation, water or air, are responsible for most sedimentary deposits. These agents, because of their fluid nature, sort the sediment during its transportation, according to size, weight, and shape of the particles. The sediments settle and therefore are in layers of greater or lesser homogeneity.

Not all deposits of "earth" are stratified, however, for some, the residual soils, have not been transported; and not all agents of transportation are fluid. Ice, for example, leaves *till* deposits with a heterogeneous assembly of particle sizes and shapes.

Most sedimentary layers have been deposited on relatively flat surfaces and are correspondingly horizontal or subhorizontal. Some strata, however, have been deposited on inclined surfaces, and the resulting inclined layers have an *initial dip* which may be as great as the angle of repose for that particular sediment.

Most strata have, broadly speaking, lens shapes, although some layers are very extensive, covering many square miles. The extent of a bed and its degree of uniformity depend upon the conditions of its deposition. The most uniform and extensive deposits are those

of the seas· lake, stream, and wind deposits are less uniform and commonly less extensive.

A gradation from coarse sediments of near-shore (shallow water) deposition to fine sediments of offshore (deeper water) deposition is common. Storm disturbances, fluctuation in supply of sediment, seasonal variations in currents, and other disturbing factors give rise to irregularities in sedimentation Thus it is that the character of sediments varies not only vertically from bed to bed, but also laterally In particular, sediments of stream origin are extremely variable both vertically and laterally.

The thickness of beds has a considerable range. In many deposits, however, beds have thicknesses of from one inch to one foot.

***Lamination and Cross-lamination.*** Within beds, or layers, minor units less than one centimeter in thickness are called *laminae*, a deposit with *laminae* is said to be *laminated* The laminae may be parallel to the bedding planes or at an angle to them. In the latter case, the sediment is said to be *cross-laminated* Cross-lamination (also called *cross-bedding* when the units involved are thicker) is

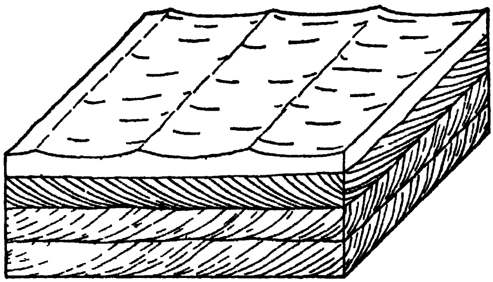


Fig 6 1 Cross bedding and ripple mark Note that the tops of the cross beds are truncated and that the bottoms tend to turn tangential to the true bedding

shown in Figs. 6-1 and 6-2. It will be observed that the tops of the cross-lamination are truncated, whereas the bottoms curve concavely, to be nearly tangential to the bedding Cross-lamination or cross-bedding is often displayed by consolidated sediments that have been folded or faulted; hence the determination of tops and bottoms of beds is possible and often of great assistance in working out the structure of deformed sediments (Fig. 9-9).

***Ripple Mark.*** Ripple marks are familiar to all who have ever seen a sand covered area Ripple mark may be caused by wind, water currents, or waves Oscillatory waves form a ripple mark, useful in determining tops and bottoms of deformed beds in much the same way as cross lamination is used This is illustrated in Fig 6-1 Ripple mark formed by currents is less useful

Fig 6 2 Cross bedded sandstone

***Primary Joints.*** Shrinkage due to water loss, compaction and settlement, slump, and other less common causes, gives rise to joints in unconsolidated and partially consolidated sediments These are characteristically short, irregular, and discontinuous In the coarser sediments the fracture zone generally does not gap open, but is a zone of different and more open packing of particles. In the fine-textured sediments, especially clays, the cracks may gap open, permitting ingress of water. These are the familiar "mud cracks" seen so frequently on clay surfaces that have been wet (Fig 6-3) The pattern is sometimes beautifully geometric.

FIG. 6-3. Mud cracks.

## MASS PROPERTIES OF COHESIONLESS MATERIALS

For convenience in discussion, but more particularly, because of notable differences in engineering properties, two classes of regolith materials are separated. These are *cohesionless soils* and *cohesive soils*.

The cohesionless materials—gravel, sand, and silt—display certain characteristic mass properties of fundamental significance in applied geology. Porosity, permeability, and dilatancy are of especial importance.

***Porosity and Permeability.*** Porosity and permeability are often confused in common speech. *Porosity* is the void space in a unit volume of material, expressed as a percentage. Porosity $n$ therefore is the void volume $V_v$ divided by the total volume $V$:

$$n = \frac{V_v}{V} \times 100$$

It is frequently convenient to use the voids ratio $e$, instead of the

percentage of voids $n$. The voids ratio $e$ is the ratio of void volume, $V_v$, to solid volume, $V_s$:

$$e = \frac{V_v}{V_s}$$

$$V_v = Vn$$

and
$$e = \frac{Vn}{V_s} = \frac{(V_s + V_v)n}{V_s} = \frac{nV_s}{V_s} + \frac{nV_v}{V_s} = n(1 + e)$$

Then

$$n = \frac{e}{1 + e} \quad \text{and} \quad e = \frac{n}{1 - n}.$$

*Permeability* as applied to soils and rocks is defined as the property which permits passage of fluids through or into the mass. The rate of movement of water through some soils, clay for example, is extremely slow, hence the term *impermeable*, which implies a negligible transmission of water. The rate of water movement depends on the viscosity of the fluid, hydraulic gradient, and coefficient of permeability.

*Viscosity of the Fluid.* The differences in groundwater density and viscosity due to temperature variations are generally so slight that they are neglected in ordinary civil engineering practice.

*Hydraulic Gradient and the Coefficient of Permeability.* The hydraulic gradient ($i$) is defined by the drop in head between two considered points of a saturated soil column through which water is moving divided by the distance ($l$) between the points. Thus $i = \frac{h}{l}$. The distance $l$ may be a straight line or a curved line; it is the distance the water travels between the considered points. In permeable granular materials with a free water table, the slope of the water table approximates the hydraulic gradient. The studies of Darcy demonstrated the relation between the hydraulic gradient and the rate of laminar flow through this type of material. This relation, known as Darcy's law may be stated (see also p. 356):

$$v = ki \quad \text{or} \quad v = \frac{kh}{l}$$

*The coefficient of permeability*, $k$(cm sec$^{-1}$), represents the velocity of percolation under a hydraulic gradient of unity, that is, through a vertical column. This coefficient is taken as a constant and must be determined or calculated in each individual case. Darcy's law has been found to hold for hydraulic gradients as low as 2 to 3 inches per mile, and up to the critical velocity, i.e., at the point where turbulent flow replaces laminar flow. There are various forms of permeameters, and their use constitutes one of the techniques of soils mechanics.

A number of formulae have been developed for estimating the permeability of well-graded relatively uniform sands from mechanical analyses. For the more irregular mixtures of particles, a satisfactory formula has not been developed.

*Factors Affecting the Coefficient of Permeability.* A variety of factors affect the coefficient of permeability. The particle arrangements, i e., porosity, grading, size of grains, and stratification are important.

*Porosity.* There is no quantitative statement relating porosity to permeability. The size, shape, and continuity of the voids determine the transmission of fluids. Without openings, there would be no permeability; but high porosity does not necessarily mean ready percolation. Some clays, for example, are, for practical consideration, impervious, though having porosities in excess of 50 per cent. As Fraser states: "No correlation can safely be made between two samples, on the basis of their porosity, unless it is certain that all their other physical properties are identical." [1]

*Grading.* Just as in the case of porosity, there is, in general, a reduction in permeability with mixtures of various grade sizes. Around the larger fragments, however, there is local increase in permeability, due to packing effects.

*Grain Size.* Larger openings, which result in more ready percolation, are found in the coarser sediments. Gravels are consequently more permeable than sands. In general, permeability decreases with

[1] Fraser, H J, "Experimental Study of the Porosity and Permeability of Clastic Sediments," *Jour. Geol.*, Vol 43, 1935, p. 966.

diminishing grain size. The rate of flow through a column of uniform spheres is taken as directly proportional to the square of the diameters of the spheres.

*Shape of Particles.* The shapes of the constituent particles of a sediment are extremely variable. The nature of the parent material, as for example, schist, shale, or granite, the amount and type of transportation, mineral cleavages, and other factors determine the grain shape. Increasing angularity generally gives greater permeability. Fraser states that "the permeability of even the most angular sands, solely because of their angularity, would probably not be greater than two or three times that of a well rounded sand." [2]

*Stratification.* Vertical variations in permeability are characteristic of sediments. Strata of different sizes of grains, of different states of packing, and different degrees of assortment and cementation, give rise to different coefficients of permeability. Commonly it is found that percolation is more ready parallel to the bedding than transverse to it.

***Dilatancy.*** The arrangement of the constituent particles of a soil gives rise to a variety of phenomena of engineering significance. Two contrasting limits of packing of mineral grains are:

1. Densest packing, in which the void space is at a minimum. This is termed *maximum density,* or *close* packing.
2. Loosest packing, in which void space is at a maximum. This is termed *minimum density,* or *open* packing.

Spherical bodies of uniform size such as marbles, for example, packed in the closest possible manner have a void space of 25.9 per cent of the total volume. In soils mechanics, the voids ratio (see p. 96) is more commonly used. In the case of the close-packed spheres under consideration, the voids ratio is 0.352. Each of the spheres is in contact with twelve of its neighbors, and lines connecting the centers of any three adjacent spheres define an equilateral triangle (Fig. 6-4). It is at once apparent that deformation of the mass, excluding deformation of the individual spheres, entails an increase in volume of

[2] *Ibid.,* p. 964.

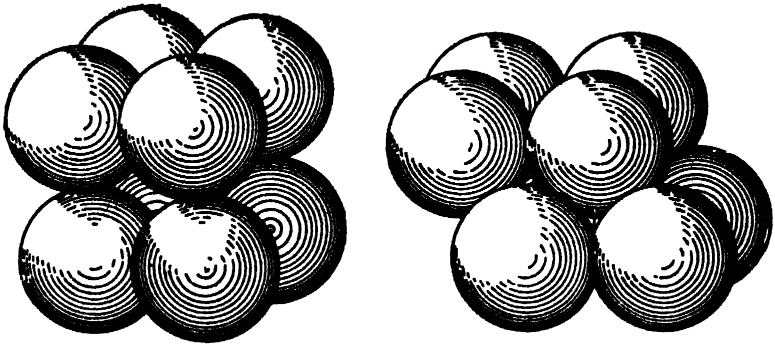


FIG 6 4. Spheres in contrasting states of packing.

voids. To deform the mass, the individual spheres must ride up over the neighboring spheres, with consequent increase in void volume.

If the same spheres are packed in the loosest possible manner, that is, so that each sphere is in contact with six of its neighbors, the volume of voids is 47.6 per cent of the whole, or the voids ratio equals 0 908. The change from densest packing to loosest packing, therefore, gives a volume increase of 41 per cent. The diameter of the spheres is immaterial if the spheres are of uniform size. If the irregular shapes of natural sand constituents are substituted for perfect spheres, the numerical values for percentage voids and voids ratio change, but the principle that there is a minimum and maximum density packing holds. The sand may be so graded that a smaller proportion of voids is present than in the closely packed uniform spheres. On the other hand, because of irregular shapes or mixtures of shapes, for example flat, angular, and spherical particles, the packing may be more open than the loosest packing possible for uniform spheres. In brief, the range of possible percentages of voids in natural rock and mineral aggregates is larger than that in the case of the uniform spheres.

Some consequences of the concept of dense and open packing are apparent:

1. If granular materials in a state approximating *open* packing are disturbed, the mass can undergo deformation, i.e., change of shape, without requiring a volume increase. Intergranular

readjustments are readily possible, and the mass tends to fail after the fashion of fluids; containing pressures do not tend to impart rigidity to the mass.

2. If granular materials in a state approximating *close* packing are deformed, an increase of volume is required. If volume increase is ,restricted, the mass takes on rigidity, confining pressures consequently impart rigidity, and the mass tends to act as a solid.
3. If closely packed granular aggregates are deformed, the increase in void space lowers the fluid or gas pressure in the deformed area, with consequent inflow of any available fluid.

*Volume Changes and Deformation.* Many sands are composed of fragments of irregular shape and size. These irregularities, together with other factors of packing, such as arching, give many sands a very open texture, so that on deformation decrease in volume occurs. If the openings are saturated with water, the rate of volume decrease is conditioned by the rate of movement of water from the deformed area. If the water does not escape readily, a hydrodynamic stress condition prevails, in which the water carries part or all of the stress, at least temporarily. Plastic failure ensues, i.e., the material fails as a fluid. The simple experiment with toy balloons described by Mead[3] illustrates this point. A toy balloon is "filled with sand and water, with the latter somewhat in excess of the amount required to saturate the sand in a condition of dense packing. The balloon so filled is soft and easily deformed *up to a certain point.* If squeezed in the hand, it suddenly becomes rigid when the volume of voids and the volume of water become equal. If more water is added, a condition is reached where the balloon is soft and easily deformed to any extent without becoming rigid." The water cannot escape because of the impervious container, hence the hydrodynamic condition.

Deformation causes reduction in fluid pressures if volume increases are involved. Any available water is drawn into the zone of deformation, and the mass becomes more fluid. This principle is

[3] Mead, W. J., "Geologic Role of Dilatancy," *Jour. Geol.*, Vol. 33, 1925, pp. 691-2.

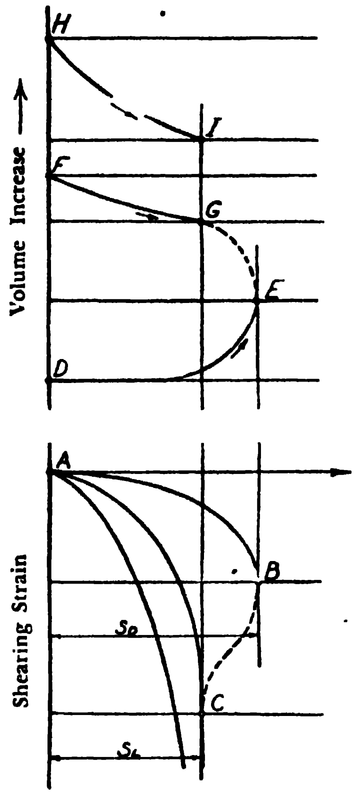
well illustrated in an experiment described by Mead.[4] A rubber cylinder, corked at both ends, is filled with sand, with the voids saturated. A glass tube, bent at right angles, inserted through a hole in one of the corks, and partly filled with colored water, serves as an indicator of volume change. Any deformation of the rubber tube lowers the level of the water in the indicator. In this experiment, a toy balloon can be substituted for the cylinder. It is filled with sand, shaken, or patted into a state approaching dense packing, and a glass tube is thrust into the neck of the balloon and secured by an elastic band. The glass rod leading into a tall narrow graduate filled with colored water serves as an indicator. Deformation of the balloon draws the water from the graduate until the sand is in open enough packing to fail plastically without volume increase.

Volume changes of sands subjected to laboratory tests are also illustrative of these principles If the test sand is densely packed, i.e., in a state requiring expansion of volume on deformation, it fails in shear as does a solid body. The zone of failure (shear) becomes a zone of open packing It is mechanically easier for the material to open up thus than for pervasive intergranular readjustments to give volume increase distributed throughout the mass. A curve showing shearing stress plotted against shearing strain in deformation of a close-packed sand is shown in Fig 6-5. Casagrande[5] says of these curves, "It will be noticed that the shearing stress reaches a maximum, $Sd$—corresponding to the point $B$ on the curve—and if the deformation is continued, the shearing stress drops again to a smaller value, $S_L$, at which value it remains constant for all further displacement During this drop in shearing stress the sand continues to expand, as shown in [Fig. 6-5] curve $E G$, finally reaching a critical density at which continuous deformation is possible at the constant shearing stress $S_L$." An explanation of these curves is in accordance with principles already developed. During the shearing, displacement increases gradually with increasing shearing stress, as the grains

[4] *Ibid.*, p. 691.

[5] Casagrande, A., "Characteristics of Cohesionless Soils," *Jour. Boston Soc. Civil Engineers*, 1935, pp. 17-18

roll and move over one another in the shearing zones, necessarily accompanied by volume increase, since the sand is initially close-packed; at point *B* on the curve, sudden failure occurs. From *B* to *C* shearing stress diminishes as the packing along the shearing zones is




A

B

FIG. 6-5. Effect of shearing on the volume of granular soil (Casagrande).

Curve *A-B*, dense sand
*A-C*, loose sand
*A*, fine-grained soil
*D-E*, dense sand
*F-G*, loose sand
*H-I*, fine-grained soil.

(By courtesy of the Boston Society of Civil Engineers)

open enough to permit easier deformation. Volume increases continue, however, up to the *G* on the curve, increases which indicate a state of open packing along the shear zones. Thus no further volume increases are required with continuing deformation.

If a very open-packed sand is subjected to similar tests, the results as plotted on Fig. 6-5 are those to be expected. As the very loose sand is deformed, the open structure gives way to a denser structure. The decrease of volume, however, is limited by that state of packing,

called by Casagrande[6] the *critical density* at which deformation can take place without requiring volume increase.

*Effects of Size and Shapes of Grains.* Adequate quantitative data are lacking for the dilational effects of grading and shapes of particles. The coarser sediments, in general, tend to be more closely packed than the sediments of fine texture. In fact, deposits of silt are almost always in a state approaching minimum density packing, whereas gravel deposits are frequently very closely packed.

Mica flakes—flat or scaly fragments such as schist, shale, or slate —in combination with rounded or angular fragments tend to give an open packing in the same way as would a combination of baseballs and shingles. The more angular and irregular the shapes, the greater the volume changes involved in the shift from dense to open packing.

*Effect of Grading.* Grading is possible, which, theoretically, will give a maximum density. The smaller sizes are required in just sufficient amount to fill in between the larger grains, with smaller sizes still to chink up the lesser voids. If each grain finds its proper place, a maximum density is secured. In nature, there are all varieties of grading, and it frequently happens that small grains lodge between larger particles in such a way that density is less rather than more.

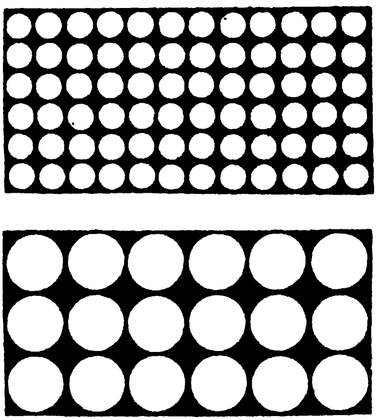


FIG. 6-6. Spheres of different sizes with same porosity.

Uniform spheres of different sizes may have the same porosity (Fig. 6-6), and mixtures of very diverse proportions of sphere sizes may also have approximately the same porosity. Nevertheless, experiments with spheres show that the porosity of a mixture of sizes is generally less than that of uniform spheres. This statement also holds for natural sands of irregular grain shape. It is obvious from the preceding discussion

[6] *Ibid.*, p. 18.

that there is no means of connecting the mechanical analysis of a granular material with its porosity.

*Effects of Depositional Agents.* The mass properties of sediments tend to be those characteristic of the dominant material. A sand with few larger pebbles, for example will display in general the properties of the sand. Around the pebbles, however, will commonly be found somewhat lesser density of packing. The state of packing, however, depends as much on the mode and conditions of deposition as it does on the mechanical composition of the material.

River-deposited sediment, generally, is very loosely packed. Rapid deposition from streams heavily charged with debris results in arching effects, which, aided by the buoying of the water, result in open packing. The finer the texture of the sediments, the greater the tendency to loose packing. River and flood-plain sediments, of the finer sand sizes and more particularly the silts, are therefore characteristically unstable foundation materials. If the sediments can drain during deposition, settlement into a closer state of packing usually results. Many beach sands, especially those deposited between high and low water, are firm and hard-packed. The vibratory effects of the waves characteristically result in very densely packed sand, if drainage is adequate. Thus they are generally stable. Wind-transported sediments are well sorted and tend to be of uniform-sized grains. They are deposited in dry condition and subject to further wind disturbance. Usually, because of the fine sizes transported by the wind and the uniformity of sizes, they are open packed. Gravels of whatever origin tend to fairly dense packing. Deformation may open them up. Glacial gravels and sands that have been shoved by ice or have slumped subsequent to deposition may be in rather open packing. Evidences of deformation are therefore of significance.

*Illustrations.* Illustrations of the principles of dilatancy are to be found on every hand. Engineering applications of the principles are both numerous and diverse. The few illustrations and applications presented here will suffice to draw attention to the practical aspects of the subject.

Quicksand is merely sand in open packing. The usual cause is a current of water passing through the material, sufficient to lift the grains into open packing; hence resistance to deformation is slight. The usual cure is either drainage or cutting off the ingress of the water. In the laboratory, demonstrations of quicksands are easily made by filling a graduate with sand and connecting a tube so that water enters the sand at the base of the graduate. A steel rod placed at the top of the container sinks of its own weight when an upward current of water causes an open-packed condition. Shutting off the water current allows the sand to settle into firm enough packing to support the rod.

A hydrodynamic condition may be induced by deformation of sand containing insufficient moisture to saturate the voids in the state of loose packing. Demonstration on a laboratory scale is easily made by placing sand in a small pile and adding water. As the pile is stirred or deformed, it appears dry. Vibration will settle the sand into closer packing, so that there is an excess of water for the void space; the mass, as a result, becomes soupy (a hydrodynamic state) and flows plastically. Vibrations caused by passing trains or of other origins have caused similar liquefaction in materials held in check by retaining walls with the development of stresses not designed for, and so may result in failure. Mudflows and landslides of certain types are similarly explained, as are certain failures of artificial embankments.

***Mineral Constituents.*** The mineral constituents of the regolith are likewise very variable. The mineral assemblage depends on the nature of the parent rock, the method of rock destruction, and on the degree of sorting and wear during transportation and subsequent processes.

***Data Needed.*** Investigations of the quantitative effects of grading, shapes, and mineral and chemical make-up upon mechanical properties are incomplete. Basic data are needed in many engineering applications. To give one example: in the field of mortar and concrete research, the effects of shapes of the sand grains and of their

mineral or chemical properties upon strength and durability are virtually uninvestigated.

## Cohesive Soils

In contrast to clean gravel or sand are soils that have a clay or colloidal organic binder, or that are dominantly clay or organic material. These are the cohesive soils that have coherence when dry and are generally sticky when wet. Clays, peats, mucks, clayey sand or silt, and boulder clays are examples.

Because much if not most engineering construction rests on soil, and because clay soils are among the most abundant of soils and frequently present troublesome problems for engineering design and construction, clays merit special consideration.

***Clay: Definition and Classification.*** In engineering usage, the term *clay* refers to a naturally occurring inorganic plastic material made up largely or wholly of particles less than 0.005 mm. in diameter. Mineralogically, *clay* implies a finely divided crystalline material essentially made up of hydrous aluminum silicates—the *clay minerals*. There are, therefore, really two principal varieties of clay: (1) deposits of clay minerals; and (2) rock flour (clay by virtue of grain size). The so-called clay minerals are alteration products of various minerals, such as feldspar or other silicates. Rock-flour clays, such as most of the glacial clays, are composed largely of finely comminuted or pulverized rock and mineral fragments. To the extent that the rock flour has been produced by grinding shales or other clay mineral bearing rocks, the rock flour clays will contain clay minerals. The state of subdivision makes identification of the fine clay minerals difficult. Identification of the different clay minerals depends very largely therefore on X-ray and thermal analysis techniques. Most "clays" contain two or more clay minerals, and practically all contain nonclay constituents of both organic and inorganic nature.

***The Clay Minerals.*** Every ceramic engineer recognizes that the modern concepts of clays are of high economic and practical value. Up to very recent time, however, the internal structure of minerals

has been of little practical interest to the civil engineer. The advances in "clay science" are finding application beyond the field of ceramics, however, and it will be worth while to indicate something of these, without going into the details of clay mineralogy.

The distinction and grouping of the clay minerals has been made possible largely through developments in X-ray techniques. Three principal groups of clay minerals are now well established. These are the *illites, montmorillonites,* and *kaolinites.*

*Illite Group.* The illite group is composed of several minerals similar to muscovite mica. Chemically, the illites are complex minerals, a general formula being

$$(OH)_4\ K_y\ (Al_4,\ FE_4,\ Mg_4)\ Si_{8\text{-}y}Al_yO_{20}$$

in which $y$ varies from 1 to 1.5.

Fig. 6-7 shows schematically the structure of illite. About 15 per cent of the silicon positions are occupied by aluminum, and the excess charge satisfied by potassium ions between the silicon sheets. The potassium ions serve as a bond between sheets, and the lattice is nonexpanding with addition of water.

Illite is perhaps the most abundant of the three groups occurring in modern marine deposits of clay. It is very abundant, also, in ancient sedimentary clays and is the dominant clay mineral of shales.

*Montmorillonite Group.* The minerals of the montmorillonite group differ from those of the illite group in having an expanding lattice structure. Chemically, the montmorillonites have the general formula:

$$(OH)_4\ (Al_y \cdot Fe_4 \cdot Mg_4)\ Si_8O_{20} \cdot nH_2O$$

The structure of montmorillonites is shown diagrammatically in Fig. 6-8. The amount of water varies; the lattice expands with addition of water, and clays of this group swell; some expand eight to ten times on soaking. Minerals of this group are especially abundant in clays derived from weathering of volcanic ash. They are present in many soils, also, and in some sedimentary clays are dominant.

*Kaolinite Group.* The kaolinite minerals have a characteristic

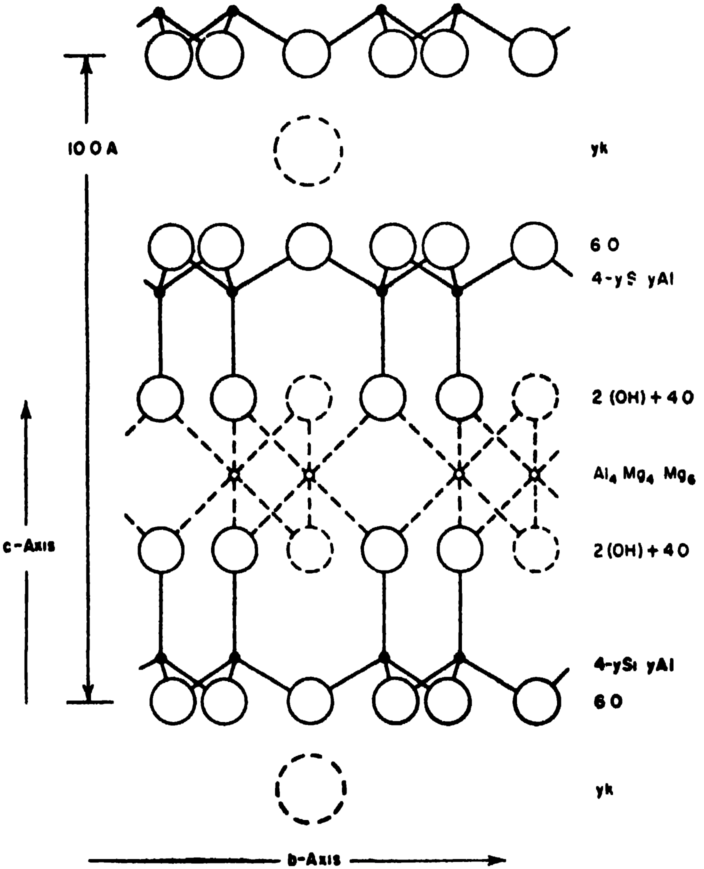



FIG. 6-7. The structure of illite, $(OH)_4K_y(Al_4, Fe_4, Mg_4, Mg_6)(Si_{8-y}Al_y)O_{20}$, y varies from 1-1.5 (After Grim)

lattice structure common to the several members of the group. Kaolinite minerals have the general chemical composition expressed by the formula:

$$(OH)_8Al_4Si_4O_{10}$$

The structure of the kaolinite group is shown schematically in Fig. 6-9. Kaolinite is widespread in modern marine clays but less abundant in these deposits than illite. Both illite and kaolinite are present and commonly intermixed in sedimentary clays. Kaolinite is the most abundant constituent of the residual clay deposits.

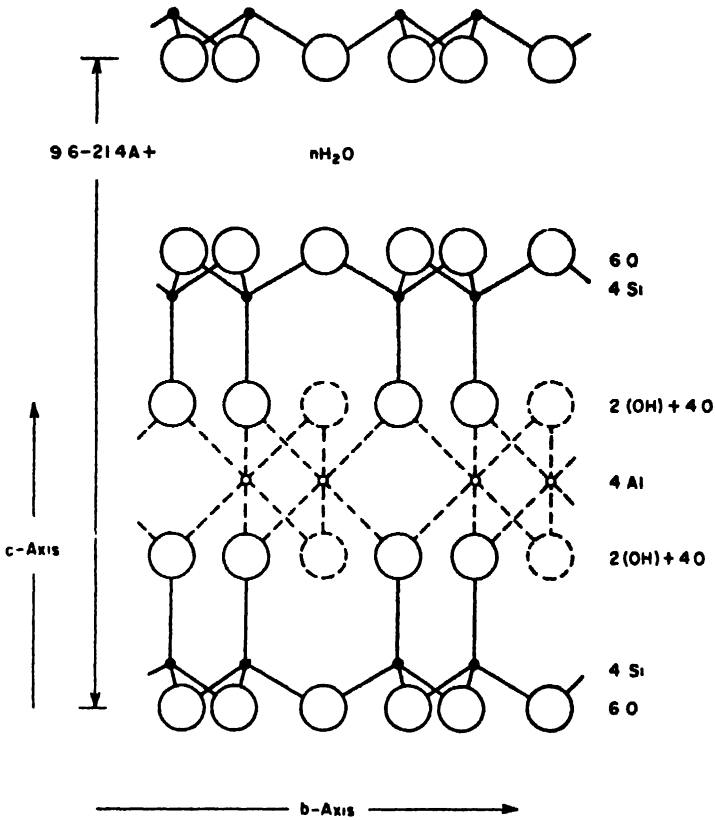



FIG. 6-8 The structure of montmorillonite $(OH)_4Al_4Si_8O_{20} \cdot nH_2O$ (After Grim)

## PROPERTIES OF CLAYS

For a variety of reasons clays do not all act alike. They differ in mineralogy as just indicated, and of course they differ in other properties—in grain size, in ion-exchange capacity, in plasticity, in permeability, in compactibility and settlement, in sensitivity, in wet and dry volumes, and in other ways as well. Most of the differences are interrelated. Because some of these differences affect both stability and cost of a structure and if neglected may cause damage or failure, the clay soils merit thorough engineering evaluation before design or construction on clay foundations, or before making use of clays as construction material.

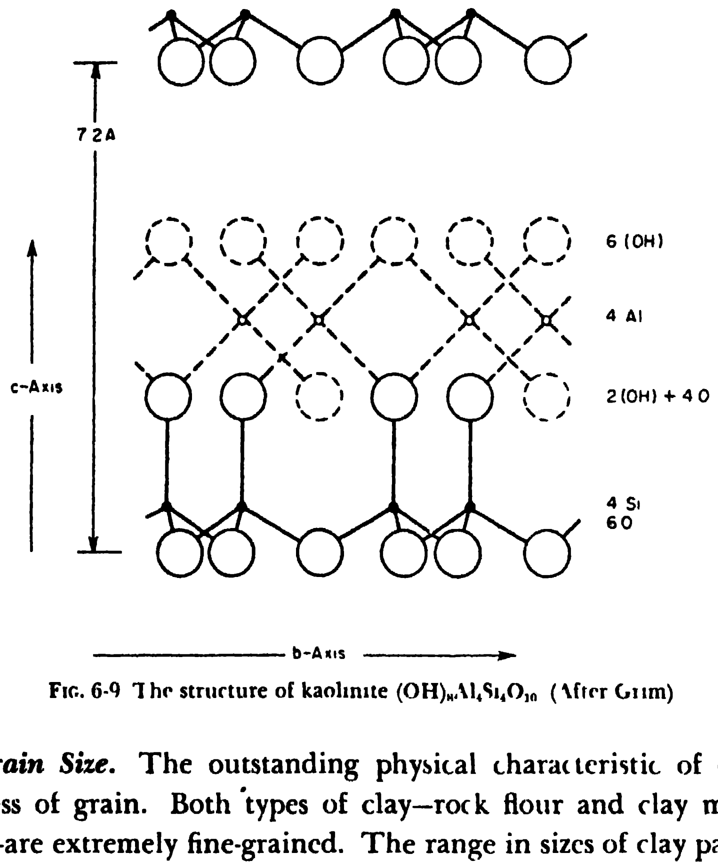



FIG. 6-9 The structure of kaolinite $(OH)_8Al_4Si_4O_{10}$ (After Grim)

***Grain Size.*** The outstanding physical characteristic of clay is fineness of grain. Both types of clay—rock flour and clay mineral clays—are extremely fine-grained. The range in sizes of clay particles is from 0.005 mm. down to colloidal dimensions, and many clay particles have diameters of less than 0.0002 mm.

Accurate determination of grain size in clays is not easy because of the tendency of clay particles to aggregate or flocculate. Montmorillonite is easily broken down to particles of less than 0.1 $\mu$ in diameter; kaolinite can be reduced to 0.1 $\mu$ only with considerable difficulty; and illite varies in ease of size reduction. The arrangement in order of generally decreasing grain size is: rock flour > kaolinite > illite > montmorillonite. The rock flour clays have a great range of grain size, but have on the average larger particle diameters than do the clay mineral clays. Indeed, most of the so-called glacial clays are really clayey silts. The influence of this state of fine sub-

division on the physical properties of the clay soils is due in considerable measure to large surface area relative to volume

***Ion Exchange.*** The very fine-textured soils are distinguished by great surface area of the particles relative to unit volume In addition to the physical mechanical effects of this state of fine subdivision, the chemistry of the constituent mineral particles varies in the fine textured soils These variations in chemical activity have marked influence upon the mass properties of a given soil, and in certain soils make it possible for the engineer to induce changes that improve the soil structure, strength, and permeability to meet some engineering specifications in some projects

It has been known for a long time that some soils have a greater capacity of ion exchange than others and that a substitution of ions may effectively alter soil properties Ion exchange is simply a process of exchanging an ion from a solid for one from a solution with which the solid is in contact and may involve either cations or anions A familiar example is the use of the mineral zeolite with exchangeable $Na^+$ to soften a high calcium hard water

$$Ca^{+2} + \underbrace{Na_2(Al_2Si_3O_{10}\cdot 2H_2O) \rightleftharpoons Ca(Al_2Si_3O_{10}\cdot 2H_2O)}_{\text{insoluble}} + 2Na^+$$

The ion exchange capacity of a soil may be expressed in milliequivalents A milliequivalent may be defined as 0 001 of the equivalent weight, or as 1 milligram of hydrogen ($H^+$) or the amount of any other cation that will displace it Other cations may be expressed as milliequivalents by changing them to their hydrogen equivalents If the cation exchange capacity is known the grams of any particular cation it can accept may be calculated

$$\text{milliequivalents per 100 g} \times \frac{\text{atomic weight of cation}}{\text{valence of cation} \times 1000} = \text{grams absorbed per 100 g of soil}$$

The structural character of the crystal lattice largely determines the extent to which such exchanges take place In clay soils the exchangeable ions may be on the edges of broken tabular shaped crys

tals due to broken bonds or perhaps to partial destruction of the clay lattice. If so, fine grinding increases the ion-exchange capacity. Or the exchangeable ions may be held on the faces of tabular crystals or within the crystal lattice rendered accessible to exchange by swelling. The organic complexes that may be present may also affect the ion exchanges. Although ion exchange as a process has long been recognized, further chemical research is required for its full utilization.

Grim gives the comparative base-exchange capacities of the three principal clay groups in milliequivalents per hundred grams as:

| | |
|---|---|
| Kaolinite | 3-15 |
| Illite | 10-40 |
| Montmorillonite | 80-150 |

Kaolin consists of a silica sheet and an alumina sheet bound together, as shown in Fig. 6-9; the sum of the plus charges of Si and Al in the sheets equals the sum of the minus charges of the O and OH ions and there are no unsatisfied electrical charges by which other ions can be held to it. Usually the exchange amounts to less than 15 milliequivalents per 100 g, held by broken bonds at edges of the particles.

Montmorillonite fundamentally consists of two silica sheets bound together by an alumina sheet (Fig. 6-8). Isomorphous substitution of tervalent Al for quadrivalent Si in the silica sheets or substitution of Mg or some other bivalent or univalent cation for $Al^{+++}$ in the alumina sheet gives rise to net residual charges that are neutralized by absorption of cations. These are the exchangeable ions. If the exchangeable ions are mostly Ca or Mg, the clay may swell to some two times its dry volume; if the exchangable ions are mostly Na, it may swell twenty or more times its dry volume.

The illite group (hydrous micas) have more isomorphous replacements than montmorillonites, with consequent higher charges; but these are largely neutralized by potassium, which is fixed and not exchangeable.

Many clay soils are admixtures of a dominant clay mineral and subordinate clay minerals with varying amounts of nonclay con-

stituents. The ion-exchange capacity commonly rises with the clay mineral content of the soil. In general it may be said that ion exchange and certain soil properties vary somewhat as follows: increases in liquid limit, plastic index, hygroscopic moisture, place density, and field moisture accompany increases in ion-exchange capacity or montmorillonite clay fraction. The permeability decreases with increased base-exchange capacity. Kaolinite, for example, may be several hundred times more permeable than a montmorillonite.

An interesting application of base exchange, illustrating also what has been said of sodium ion bearing clays, is given by Winterkorn:

> A classical example of good engineering has been supplied by the engineer in charge for the construction of the fresh-water lake on Treasure Island in San Francisco Bay The bottom of the ? acre lagoon had been covered with a 10-inch compacted clay lining to prevent seepage loss. However, a loss of 1 inch of water per day was experienced—an amount which threatened to prohibit maintaining the lagoon. The problem was solved practically by filling the lake with saline water from the bay, which resulted in changing the relatively pervious natural soil into a Na soil through ion exchange. The saline water was then removed, and the lagoon was filled with fresh water. After the excess electrolytes had been washed out of the clay layer, it assumed the low permeability of a true Na soil As a consequence, the loss of water per day was reduced from 1 inch to 0.1 inch.[7]

Use of the ion-exchange principle will undoubtedly increase in engineering practice involving upstream dam aprons, earth-core dams, and similar projects.

***Consolidation.*** Because of the open packing of clay particles and the relatively high water content, clays are especially liable to compaction or consolidation under load. The consolidation of soils involves a loss of pore space, with corresponding loss of water or gas contained in the voids. To some degree at least, consolidation involves a rearrangement of the component particles of the soil. Be-

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[7] Winterkorn, H. F., "Application of Modern Clay Research in Construction Engineering," *Jour. Geol.* Vol. 50, 1942, p 297.

cause most clays are near the saturation point at a given voids ratio, a reduction of voids commonly requires expulsion of water. The rate of consolidation or compaction therefore varies directly with the permeability and load imposed and inversely with the distance the water has to travel to escape from the bed. Because of the low permeability of clays in general, the delay in reaching equilibrium after loading may be years. Decreasing permeability with expulsion of water and closing up of voids slows the settlement rates. To hasten consolidation, vertical sand drains are often installed.

At many places the weight of overlying soil and water resting on a given clay layer is as great as it ever has been in the past. The clay is "normally" loaded. At other places, the clay may have been more deeply buried than at present; erosion may have stripped off a part of the load. Glacial ice may have advanced over the soil, loading it beyond the present existing load. Again, formerly exposed at the surface, the top few feet of a now buried clay layer may have been dried out or desiccated; for example, an intermittent lake bed might be thoroughly dried out in the dry season, and subsequently covered with wind- or water-laid sediments. In all of these instances clay has been consolidated by conditions or loads not now existing at that place—the soil is "preconsolidated." Thus evidences of advance of an ice sheet over a clay, or of the magnitude of erosion of overlying material, or of exposure to drying (for example by the recognition of disconformity—see p. 191) may be locally discovered by geologic observation. This type of geological deduction permits some inferences as to probable soil stability, for undisturbed preconsolidated soils are unlikely to give much consolidation trouble unless structures impose loads approximating those that produced the preconsolidation. Although relief of load may cause a partial re-expansion of the soil, preconsolidated soils are much less troublesome than normally loaded soils, and locally they have made structures possible that could not have been supported on a soil of the same constituents that had not been so conditioned. Increased shearing strength as well as confined bearing strength are residuals of preconsolidation. On the other hand, heaves in the bottoms of deep cuts in precon-

solidated soils that were heavily loaded in a former cycle may be very troublesome.

The most cited and perhaps the most spectacular settlements due to clay consolidation occur in Mexico City, which is underlain by thick montmorillonite clay beds, tuffs, gravel, sand, silty clay, and silty sand. Large buildings have settled at an average rate of 5 inches per year, and as much as a total of 10 feet. The clay may contain five to seven times its dry weight of water, and the voids ratios may be as high as 14.0. These amounts and rates are of course far from usual.

Because of the close correlation of consolidation effects with permeability, it is apparent that the general order, glacial-rock flour clays > kaolinite > illite > montmorillonite, holds for consolidation of clay soils

*Shrinkage.* Most natural clay soils shrink on drying as a result of diminution of void space. There is however, a limit, called the *shrinkage limit,* to this type of compaction or consolidation, which is defined numerically for a given soil as that water content below which no further volume loss takes place with continued water loss. Shrinkage may be due to loss of water from around the grains, or from loss of water from the lattices of clay minerals. Shrinkage is greater for clays of montmorillonite content, therefore, than for other types of clay soils.

Shrinkage of clays is of especial concern to ceramic engineers. As a form of preconsolidation, however, desiccation may be highly significant to the civil engineer. Certain types of deposit—for example, those of flood plains, intermittent lakes, or the upper parts of some tidal flats that are alternately flooded and dried out—may be composed of successive layers of partially consolidated (in this sense, preconsolidation) sediment. Shrinkage imparts a measure of strength by consolidation to some soils that otherwise might be unsuitable as foundations. On the other hand, shrinkage may cause failures by withdrawing support. In California, for example, recession of a clay as much as 2½ inches from adjacent concrete has caused differential settlements and damage to concrete pavements.

The effects of desiccation, exceptionally, may extend to depths of 25 feet or more.

*Swelling.* Adsorption of water by clay soils increases volume in a manner essentially the reverse of shrinkage, although the structure of the soil is usually so modified in shrinkage that not all of the pre-shrinkage volume is recovered. Swelling is also a result of imbibition of water into the lattices of some of the clay minerals Some montmorillonite clays—*bentonite*, an altered volcanic ash, for example—may swell as much as 1600 per cent or more on prolonged soaking, whereas kaolinite clays commonly swell less than 10 per cent.

Swelling pressures develop as a result of the hydration This is especially true where a swelling clay has been strongly preconsolidated. Fig 6-10 shows uplift of buildings in Pretoria, South Africa,

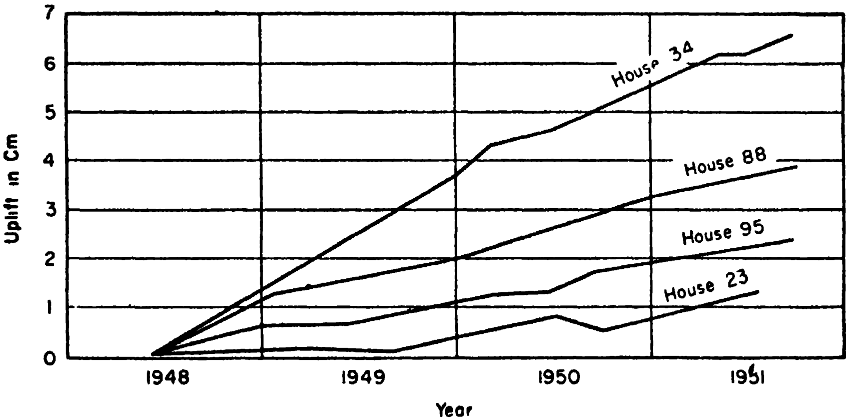


Fig 6 10 Uplift of buildings by expansion of illite clay as the result of hydration Pretoria, South Africa (After Jennings)

due to expansion of illite clays Damaging uplift near the town of Ontario in Oregon also took place, with seepage of irrigation water and runoff into a $Na^+$ bentonite soil which caused an uplift of 1 foot in three years. In this Oregon failure, uplift pressures were on the order of 50 pounds per square inch. Expansion of the Eagle Ford Shale (Texas), a montmorillonite compaction shale, gave uplift pressures of more than 200 pounds per square inch.

Pavements, canal linings, basements, and light structures of vari-

ous kinds may be damaged by clay soil swelling. A variety of engineering measures may be taken to minimize anticipated effects. One of the most effective ways is introduction of stabilizing cations into the worst offenders, the Na clays.

***Plasticity.*** Plasticity is the property of deforming nonelastically without change of volume or visible rupture. In clays, plasticity is conditioned to a large degree by the water content, the manner in which the water is held, and the size and shape of the clay particles. Fineness of grain implies large surface areas relative to volume. The increase of surface area with decrease in size is readily visualized by imagining a cubic centimeter of quartz successively subdivided into smaller and smaller cubes thus:

| | | | | | |
|---|---|---|---|---|---|
| | 1 | cc | cube quartz | = 6 | sq. cm. surface |
| cut into | 0.1 | cc. | cubes | = 60 | sq. cm. surface |
| cut into | .01 | cc | cubes | = 600 | sq. cm surface |
| cut into | .001 | cc | cubes | = 6,000 | sq cm. surface |
| cut into | .0001 | cc | cubes | = 60,000 | sq. cm. surface |

Clay-sized particles, because of the large surface areas, have adsorbed films of moisture and gases that are difficult or impossible to completely drive off below a red heat. In the size range of the clays, the adsorbed moisture films or envelopes about the particles make up a considerable portion of the volume. These envelopes, so far as the water is in liquid state, are readily deformed. This characteristic, together with the tensile strength of the water (which may be considerable), accounts in large measure for the plasticity or molding qualities of many clays when wet. Thus in a clay of given mineral composition, decrease in grain size gives an increase in plasticity because the water envelopes of the individual particles become relatively thicker with respect to diameter, and the layer of "oriented" or rigid water about the particles becomes correspondingly less effective. Scaly shapes of clay constituents, such as the clay minerals, micas, and chlorites, also probably play a part in causing plasticity. Because of the envelopes surrounding the individual clay particles, clays are always in a state of open packing; and although they may

take a "set" or become in part consolidated, on disturbance of the "set" they tend to fail plastically.

A measure of plasticity, called the *plastic index*, $I_p$, is defined as the difference between the water content at which the clay has but slight resistance to deformation (called the *liquid limit*, $L_w$) and the water content at which it loses plasticity or crumbles when rolled into thin threads (the *plastic limit*, $P_w$):

$$I_p = L_w - P_w$$

The so-called *plastic clays* generally have an $I_p > 15$. The limits $L_w$ and $P_w$ are called the Atterberg limits, and the water is indicated as percentage of dry weight. The *liquid index*, $L_i$, is:

$$L_i = \frac{w - P_w}{L_w - P_w}$$

where $w$ is the water content of the sediment *in situ*. Table 6-1 shows some representative values for different kinds of clays:

TABLE 6.1. SOME REPRESENTATIVE ATTERBERG LIMITS FOR CLAYS

| Clay | Plastic Limit | Liquid Limit | Plastic Index |
|---|---|---|---|
| Rock Flour | 20 | 40 | 20 |
| Kaolinite | 37 | 65 | 28 |
| Illite | 50 | 120 | 70 |
| Montmorillonite | | | |
| $Na^+$ | 97 | 700 | 603 |
| $Ca^{++}$ | 72 | 124 | 52 |

Mineralogically, the montmorillonites are the most plastic; when carrying $Na^+$, this variety has a liquid limit ten times that of kaolinite. Thus it appears probable that the nature of the crystal lattices of the clay minerals accounts in part for differences in plasticity. The expanding lattice of montmorillonite permits the entry of a relatively large amount of water. In montmorillonites with $Ca^{++}$, the bonding action of the cation is relatively strong, so that less swelling on soaking occurs; whereas in a $Na^+$ montmorillonite, the relatively weaker cation bond permits thicker water sheets. In

the illites and kaolinites, water does not penetrate between the basal planes of the unit cells. Hence the plasticity of most montmorillonite clays is greater than that of kaolinite or illite clays. As little as 5 per cent montmorillonite in a clay induces a large increase in plasticity.

In a clay of given mineral composition, decrease in grain size results in an increase in plasticity because the water envelopes of the individual particles become thicker with respect to diameter, and the layer of "oriented" or rigid water about the particles, becomes correspondingly less effective.

It is a matter of observation that Atterberg limits for different samples from clay deposits which are similar texturally and mineralogically tend to define a straight line with a slope roughly parallel to the *A line* when plotted on a graph similar to that of Fig 6-11.

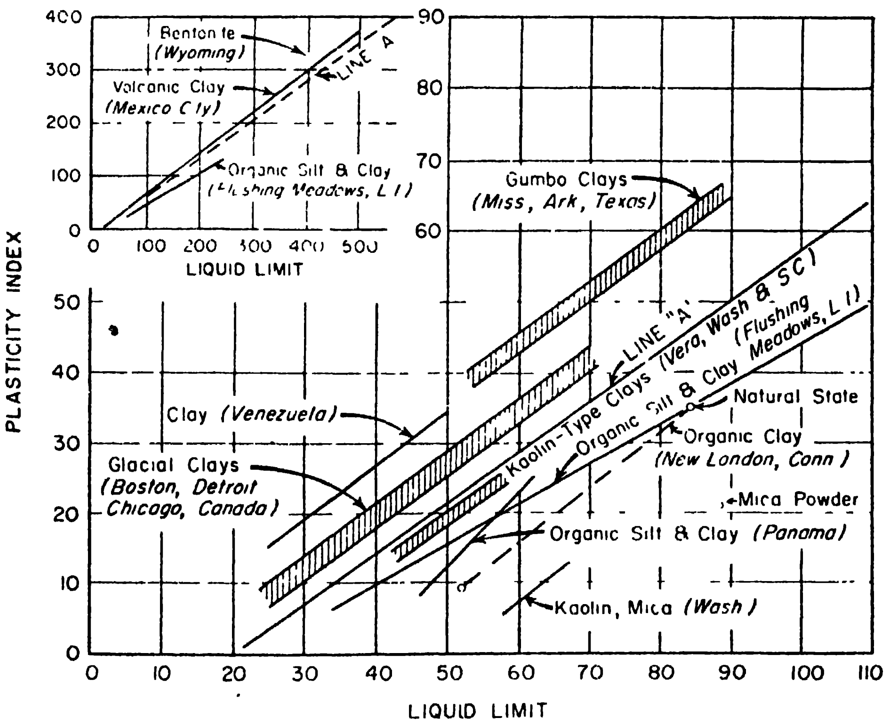


FIG. 6 11. A classification of clays according to plasticity index and liquid limit. (After A. Casagrande)

If the plots of these values of different samples fall in widely different lines, probably the samples are of geologically different deposits. Classification of clays on this type of diagram is useful for engineering prediction based on comparison with plastic soils that have been met in previous engineering experience.

A few generalizations relating plastic qualities to other characteristics may be useful in summary:

1. The more plastic the soil (i.e., the higher the $I_p$), the greater the probability of failure under load, and the lower the angle of shearing resistance.
2. Soils of similar geologic history and similar liquid limit may be expected to undergo similar compression under load.
3. Soils of similar history and liquid limit differ with the plastic limit thus: if $P_w$ of one soil is greater than $P_w$ of a second with similar $L_w$ (i.e., the second has a larger $I_p$), compressibility is about the same, but the permeability of the second is less, and it therefore compacts more slowly and has a greater dry strength.
4. If soils of similar geologic history have equal plastic indices, but one has a greater liquid limit $L_w$ than a second, the one with the higher $L_w$ has the greater compactibility, greater permeability, and more rapid rate of compaction—and probably a lower dry strength.

***Permeability.*** Clays have low permeability. The interparticle openings are too small to permit ready circulation. In fact, the greatest amount of water that penetrates a clay mass probably enters through shrinkage or desiccation cracks. Nevertheless the interparticle permeability of some clays is greater than that of others. This variation is due in large measure to the structure of the clay soil and the degree of arrangement and rigidity of adsorbed water. Aggregates of clay minerals, too, are more permeable than dispersed systems.

An improvement in a clay soil is described by Lamb,[8] who re-

[8] Lamb, T. W., "Improvement of Soil Properties with Dispersants," *Jour. Boston Soc. C. E.*, Vol. 41, 1954, pp. 184-207.

ports that a 1-foot thick blanket of clay-silt (30 per cent illite) treated with 0.1% sodium tetraphosphate was as effective in sealing the bottom of a 22 million gallon sulfite storage lagoon against leakage as a 10-foot thick blanket of the untreated soil.

Clays that carry an adsorbed $Na^+$ ion are less permeable than the $Ca^{++}$ clays, probably because they have a higher capacity for holding water in an arranged or rigid state. The montmorillonite clays are in general therefore less permeable than other types. Kaolinite clays, with grains 100 to 1000 times the diameter of montmorillonite particles and with little "rigid" water, are more permeable than the montmorillonite clays. The illites are intermediate. The glacial-marine clays (rock flour clays) are somewhat more permeable than are the kaolinite clays, and the glacial-lacustrine clays (varved clay-silts) generally more permeable than the marine clays. Representative values showing these variations are:

| | |
|---|---|
| Varved (lake) clay | $10^{-4}$ cm/sec |
| Marine-glacial clay | $10^{-5}$ cm/sec |
| Kaolinite clay | $10^{-6}$ cm/sec |
| Illite clay | $10^{-7}$ cm/sec |
| Montmorillonite | $10^{-8}$ cm/sec |

***Sensitivity.*** The clay particles bear similar electric charges, which cause mutual repulsion as they are carried along in a water current or dispersed in a water body. Neutralization of these charges permits coagulation, and floccules of clay settle out. Neutralization may be brought about by electrolytes or oppositely charged colloids. The result is actually a form of precipitation, and most marine clays are in this sense truly precipitates. Substances tending to keep the colloidal particles in suspension are called *peptizers*. Tannic acid and many other organic acids act in this way. Streams and other fresh waters more commonly carry peptizers than flocculators. The settling of clay-size particles in fresh waters is very slow, since flocculating agents are generally absent. Whether the sedimentation results from flocculation or from settling of dispersed particles with minor flocculation, there is a large amount of entrapped water, and not uncommonly clays have as much as 90 per cent or more of contained water.

A very open structure of honeycomb type is shown diagrammatically in Fig. 6-12.

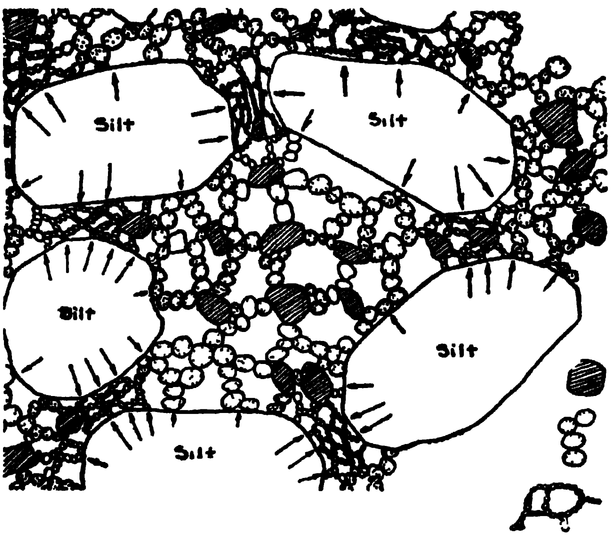


FIG. 6-12 Structure of undisturbed marine clay, Casagrande. (Courtesy of the Boston Society of Civil Engineers)

Because of the envelopes of water surrounding individual clay particles, clays are always in a state of open packing; and although they may take a "set" or become in part consolidated, on disturbance of this "set" they are weakened and tend to fail plastically. A comparison of compressive strengths of unconfined clays in undisturbed and remolded states is expressed as *sensitivity* of the clay: sensitivity is the ratio of these unconfined compressive strengths.

$$\frac{\text{Compressive strength, undisturbed}}{\text{Compressive strength, remolded}} = \text{sensitivity}$$

The values can be grouped as low, medium, high, and quick:

| | | |
|---|---|---|
| $S_t$ | 1-4 | Low sensitivity |
| $S_t$ | 4-8 | Medium sensitivity |
| $S_t$ | >8 | High sensitivity |
| $S_t$ | >16 | Quick clay |

In a general way the sensitivity increases with liquid index (p. 118). Clays with a low liquid index ($L_i < 1$) are generally of low sensitivity.

The "set" of clays is probably to be explained as the sum of the results of three processes acting on the clay. Casagrande[9] has explained one of these as due to greater consolidation in the narrower confines between the larger grains than in the more open spaces (see Fig. 6-12). Thus because of the uneven stress distribution, the clay between the arches remains soft, whereas the more confined parts are consolidated. Disturbance of this "set" condition destroys the structure and impairs its quality as foundation material. The second contribution to the initial set of clays is the thixotropic hardening that is developed in varying degrees by different clays. As previously indicated, it appears probable that intermolecular forces cause a fixation or orientation of part of the water, which adheres to the clay particles and serves as a cement. Disturbance of the clay breaks a part of this "rigid" water cement into liquid, with loss of strength. Clays may recover this part of strength lost by remolding or disturbance

A third factor is the presence of some mineral cement which has been deposited along with the clay or has precipitated out of water contained in the clay. Calcium carbonate, silica, or iron oxides may serve as cements that give strength to clays in proportion to their abundance in the soil. Organic colloids also may act in this binding capacity. To what extent clays recover from disturbance of these strength-imparting cements depends upon the type of cementing agent and time involved. In considerable measure this loss of strength may be recovered in time, although at a delayed rate. Data are lacking on which to base estimates.

In view of these facts of clay behavior, laboratory tests of remolded clay are of limited value.

Remolding and consequent disturbance of set are also effects of pile driving. The structure of the clay adjacent to the pile is adversely effected, with consequent large increase in compressibility. Piles carry by far the greater part of their load by skin friction. Casagrande states that in clay the point resistance at failure never

[9] Casagrande, A., "The Structure of Clay and Its Importance in Foundation Engineering," *Jour. Boston Soc. Civil Eng*, 1932.

exceeds 20 per cent of the total load. Piles driven in clay, therefore, which do not reach a competent substratum tend to increase both the rate and amount of settlement of a superincumbent load. Where other structures are close by, as in city construction, reduction in lateral support due to adjacent pile driving may cause renewed settlement.

An instructive illustration in this connection is given by Casagrande[10] Fig. 6-13, in which *A* gives the load distribution of a group

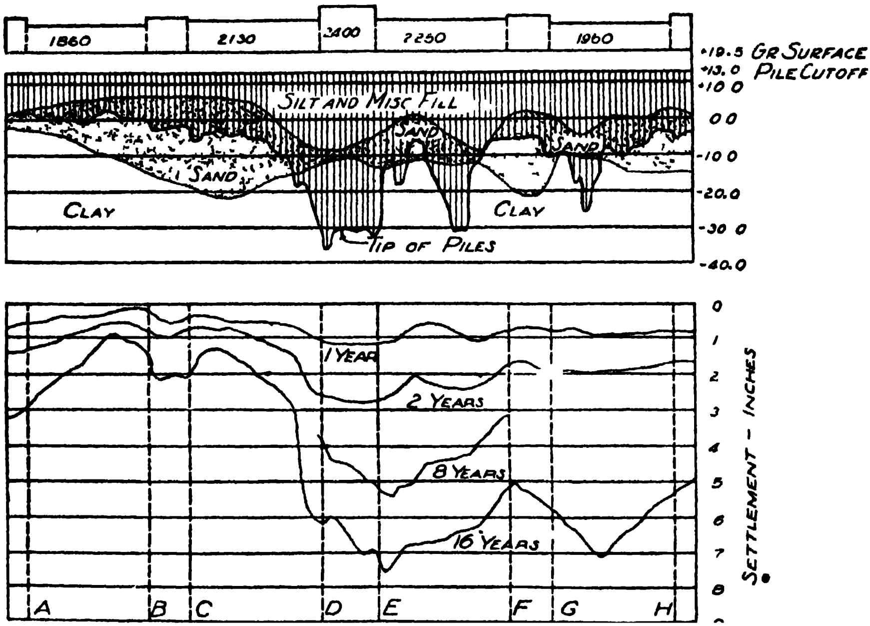


FIG. 6 13 Settlement of a group of buildings founded on Boston Clay, Casagrande. (Courtesy of the Boston Society of Civil Engineers)

of Boston buildings founded on clay, the soil profile, and depths to which piles were driven. Figure 6-14 *B* shows the settlements at different periods after construction.

"The clay is fairly homogeneous and approximately of uniform compressibility, except for a very soft layer above elevation —10 at the extreme left. The thickness of the compressible clay layer varies between 55 and 85 feet.

[10] *Ibid*

"Taking into consideration the difference in thickness of the clay layer and differences in load the settlement curve after sixteen years should show much less variations, and the maximum settlement should be smaller than is represented by the actually observed settlement curve. Due to the disturbance of the clay structure, the settlement is much larger in those sections where the piles penetrate into the clay. The effect of the disturbance spreads a short distance beyond the region of disturbance, so that the undisturbed regions between zones of disturbance show also larger settlements. This is

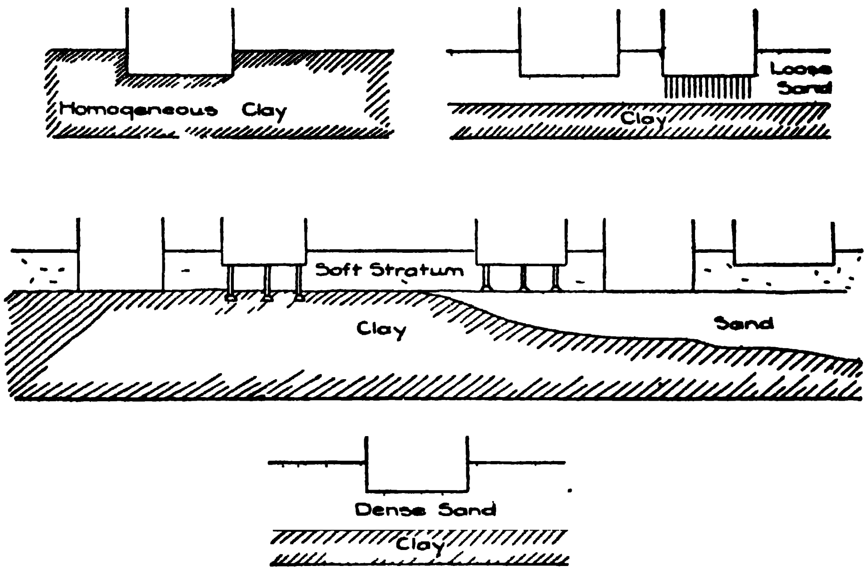


FIG 6 14 Building foundations on clay

partially due to decrease in lateral support of the undisturbed clay mass.

"The considerable settlement on the extreme left is due to the less consolidated clay above elevation —10 and a slight load concentration. The depression between sections B and C is due to a load concentration. The sudden increase of subsidence to the left of section D can only partially be explained by the larger load. The fact that the sudden drop coincides with the border line of undisturbed and disturbed soil, and not with section D where the load

increase starts, is a remarkable evidence for the disturbing effect of piles." [11]

Good engineering practices in founding structures under some typical conditions involving clay substrata are summed up in Fig. 6-14. The student should analyze the considerations involved for each condition of this figure. The article by Skempton (1955) gives an excellent discussion and varied case histories of this type of foundation problem.

## PEATS AND MUCKS

Peat is an accumulation of vegetable remains buried in vegetable debris below the water table so that decomposition is only partial. Mucks are similarly formed in areas of swampy character, but with relatively high content of mineral matter. The mineral matter of peats and mucks in part is derived from the vegetable matter, but to a larger extent is deposited by wind or from suspension in water that floods the swamp from time to time. There is complete gradation between peats, mucks, organic clays, and nonorganic clays. "Humification," largely by bacteria, produces the black, cheesy, structureless soil of many swamp excavations.

Peat and muck soils vary in characteristics according to the clay-silt content and the kind and state of humification. In general, these soils have a low density, high porosity, low permeability, and extremely high water content. The water content is often several hundred per cent. This type of soil, therefore, is one of extreme compressibility. Compacted, however, it has little tendency to expand on release of load. Because much of the water is capillary, squeezing or loading is ineffective in reducing the water content below certain limits.

In foundation work, the peat or muck must generally be removed by excavation, or displaced by loading. Settlements under fills can be hastened by blasting if the deposit has considerable thickness. In laying fills on peats or mucks, excavation to the water table removes possible temporary support and thus hastens settlement. Vane tests on peats often show a range of 1 to 3 pounds to the square inch.

[11] *Ibid.*

Roots and fibers probably contribute to this strength, and small loads cause large settlements.

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STRATIFIED SEDIMENTARY ROCKS. (GASPÉ PENINSULA, QUEBEC.)

# CHAPTER VII

# THE CONSOLIDATED SEDIMENTS

ALTHOUGH, TECHNICALLY, THE UNCONSOLIDATED SEDIments are rock, to most people, the term *rock* connotes some degree of coherence or consolidation. Some sediments are consolidated soon after deposition; other deposits may exist for millions of years in the unconsolidated state, and there are all gradations and degrees of consolidation. The aggregate changes occurring between deposition and consolidation are termed *diagenesis*.

## CONSOLIDATION

During diagenesis, coherence is developed by compaction and dehydration, cementation, and recrystallization. Although one of these consolidating processes may be dominant locally, commonly the three are concurrently at work.

***Compaction and Dehydration.*** With burial under additional deposits, settling under load takes place with the expulsion of excess water. Ultimately, cohesive bonds are established or strengthened, and the sediment gains an appreciable degree of solidity. This type of consolidation operates most effectively on the finer-grained sediments of the clay group, upon mixtures of grade sizes containing a clay fraction, or upon other sedimentary types with a colloidal content. The transformation of clay to shale or that of peat to coal are familiar examples.

***Cementation.*** In deposits through which water can circulate, dissolved mineral matter may be precipitated out, sticking the grains or fragments together, and reducing the void space. The mineral

cements may be introduced into the mass from outside by circulating water or may be derived from within the mass by solution or alteration of some of its constituent parts. Three common mineral cements are: silica (quartz), calcium carbonate (calcite), and iron oxides in various degrees of hydration. In the discussion of chemical weathering it was shown that these three substances—silica, calcium carbonate, and iron oxides—are abundantly produced by the alteration of most types of rocks. Silica makes the strongest and most durable of the mineral cements, with iron oxide and calcite somewhat less effective.

***Recrystallization.*** The components of a sediment may crystallize or recrystallize, giving coherence to the rock. Water is expelled, void space reduced, and the bonds between the new crystals established. These processes are assisted by the development of an interlocking fabric or grain. Lime deposits recrystallize rather readily, and many limestones that have suffered no squeezing other than that of superincumbent load have recrystallized completely. Recrystallization is probably initiated very early in the history of clays, also, with the development of finely divided white mica. In the formation of clay minerals by weathering, the potash liberated seems to have an affinity for the clay and tends to remain associated with it. During recrystallization, chemical recombination of the potassium, silica, alumina, and some water forms the white mica, sericite. It has been shown that colloidal or soluble silica is liberated in the alteration of silicate minerals. In so far as this is deposited with the clays and subsequently crystallized into quartz, it serves as a binding agent.

## CLASSIFICATION

The classification of mixtures of clay, silt, and sand, according to the Maine Geological Survey soils triangle, has been given as Fig. 5-2 (page 77). For the naming of the consolidated equivalents, however, the geologist uses a somewhat simpler scheme. The practice is to name the rock according to the dominant material, prefixing terms descriptive of the minor ingredients. Thus, a sandstone with a considerable clay content is termed an *argillaceous*, or *clayey*,

sandstone. In the prefixes, *argillaceous* is commonly substituted for clayey, and *arenaceous* for sandy. In addition to the clastic fragmental components, a calcium carbonate content frequently must be considered in naming the rock. Thus, a rock may be limestone,

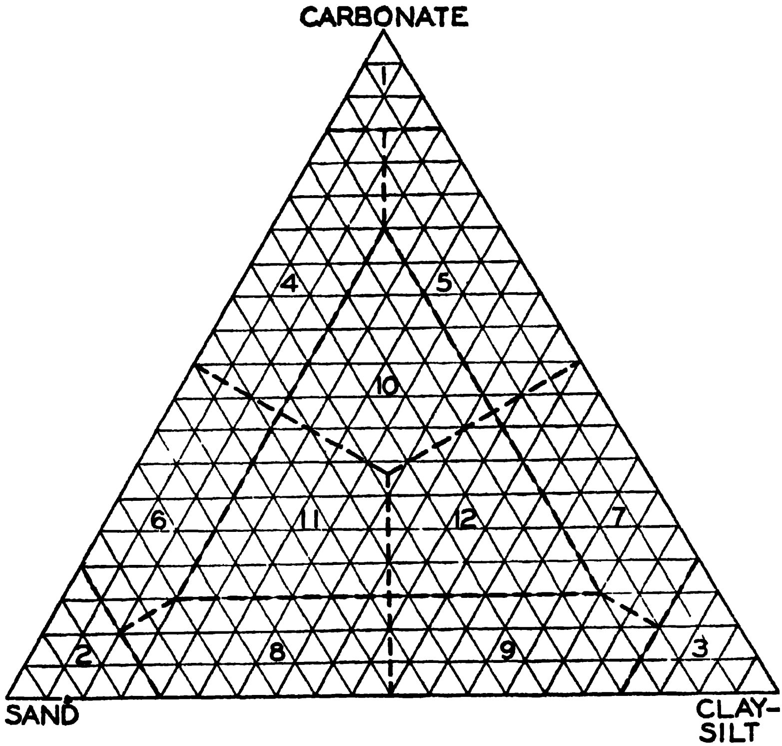


FIG. 7-1. A classification scheme for common sediments.

KEY

1. Limestone
2. Sandstone
3. Shale
4. Sandy limestone
5. Argillaceous limestone
6. Calcareous sandstone
7. Calcareous shale
8. Argillaceous sandstone
9. Sandy shale
10. Sandy argillaceous limestone
11. Calcareous argillaceous sandstone
12. Calcareous sandy shale.

arenaceous limestone, calcareous sandstone, or calcareous shale. The classification scheme proposed in Fig. 7-1 shows in a suggestive way the application of the nomenclature practice, although the limits of the groups, as diagramed, are not generally agreed upon, and

TABLE 7.1. A CLASSIFICATION OF SEDIMENTARY ROCKS *

| | Nature of Sediments | | Sedimentary Rocks | | |
|---|---|---|---|---|---|
| DOMINANTLY FRAGMENTAL | Angular particles more than 2 mm in greatest dimension | Rubble composed of sharpstones | SHARPSTONE | CONGLOMERATE | |
| | Rounded particles more than 2 mm. in greatest dimension | Gravel composed of roundstones | ROUNDSTONE | | |
| | Angular and rounded particles of rocks and minerals ranging in greatest dimension from 2 mm. to 0.1 mm. | Volcanic fragments = Tuff<br>Mixture of rock and mineral fragments<br>Quartz + Feldspar<br>Quartz + other minerals in large amount<br>Quartz + other minerals in small amount | TUFFSTONE<br>GRAYWACKE<br>ARKOSE | SANDSTONE | |
| | Rock and mineral particles ranging in greatest dimension from 0.1 mm. to 0.001 mm. and colloidal particles less than 0.001 mm. in greatest dimension | Volcanic ash<br>Silt particles — 0.1 to 0.01 mm.<br>Clay minerals less than 0.01 mm.<br>Silt + Clay + Water = Mud | ASHSTONE<br>SILTSTONE<br>CLAYSTONE<br>MUDSTONE | SHALE | |
| FRAGMENTAL | $Fe^{II}$ and $Fe^{III}$ compounds precipitated inorganically and organically as concretions, nodules and layers | Iron concretions | Concretionary | IRONSTONE | PRECIPITATED |
| | Impurities commonly present in the layers | Iron compounds + mud, silica, etc. | Precipitated | | |
| | Siliceous inorganic fragments less than 2 mm. in greatest dimension | Inorganic fragments | Fragmental | SILICASTONE | |
| | Siliceous organic hard parts and their fragments | Diatom frustules, radiolarian skeletons and sponge spicules | | | |
| | Silica precipitated as oölites, pisolites, etc. | Siliceous concretions | Concretionary | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| PARTLY | Silica precipitated from suspensions and solutions | Chert, flint, sinter, etc. | | Precipitated | | |
| | Plant structures — spores, fronds, leaves, wood, etc. | Plant debris; inorganic impurities | | | COAL | |
| | Inorganic sediment | | | | | |
| | Waxes, resins, etc. from decomposition of plants | Plant fluids | | | | |
| | Calcite and Aragonite fragments<br>Calcareous organic hard parts—shells, exoskeletons, plates, spines, and fragments | | | Fragmental | LIMESTONE | PARTLY |
| | Organically and inorganically precipitated concretions | | | Concretionary | | |
| | Inorganically precipitated $CaCO_3$—Evaporation, etc.<br>Organically precipitated $CaCO_3$—(1) by $NH_3$ from decomposition; (2) loss of $CO_2$ to plants; etc. | | | Precipitated | | |
| | | | | Recrystallized | | |
| | Dolomite fragments<br>Dolomitized organic hard parts | | | Fragmental | DOLOSTONE | |
| | Dolomitic concretions | | | Concretionary | | |
| | Organically precipitated dolomite<br>Inorganically precipitated dolomite | | | Precipitated | | |
| POSSIBLY FRAGMENTAL | Fragments of anhydrite, gypsum, halite, alkali, nitrate caliche, etc. | | | Fragmental | SALINASTONE | DOMINANTLY PRECIPITATED |
| | Evaporites — minerals precipitated during evaporation of saline waters | Anhydrite<br>Gypsum<br>Chlorides<br>Nitrates<br>Other rare salts | Precipitated | ANHYDROCK<br>GYPROCK | | |

current usage is quite loose. It will be noted that there are other sedimentary rock types than those shown in the figure; the diagramed types, however, constitute the bulk of sedimentary rocks commonly encountered. A more complete classification is shown by Table 7.1.

### Conglomerates and Breccias

Gravels are deposited for the most part by water. The two common environments of deposition are the shallow marine waters and swift-flowing streams. The interstices between the pebbles are commonly filled with sand or finer material. Waters circulating through gravel deposits may precipitate out silica, calcium carbonate, or iron oxides, which act as cements binding the gravels together into *conglomerates.* An argillaceous content may become indurated into cementing material by compaction and dehydration. Widespread conglomerates of no considerable thickness have frequently been formed in the geologic past by the gradual encroachment of seas over weathered land surfaces. The pebbles which make up conglomerates may be of a variety of rock types; or more rarely they may consist of one type of rock. A number of subvarieties of conglomerates are recognized, such as *tillite,* a consolidated unstratified glacial deposit; *fanglomerate,* a consolidated coarse alluvial fan deposit; and others.

If the pebbles or fragments composing the conglomeratic rock are decidedly angular, the result of rock breaking, the term *breccia* is commonly applied. The angularity implies relatively slight transportation. The consolidation of the angular debris which accumulates at the base of steep cliffs, for example, gives rise to *talus breccia.* Weathering may leave angular fragments at the surface which subsequently become consolidated into breccias. Not all breccias, however are of sedimentary origin. Many breccias have been formed by volcanic eruptions. These are called *volcanic breccias.* The intrusion of igneous magmas is sometimes accompanied by rock breaking in such a way that the fragments become imbedded in the consolidating magma, thus giving rise to *intrusion breccias.* Overpowering

stresses may cause the rocks affected to fracture and break, particularly along zones of dislocation called faults. These shatter zones, subsequently cemented with vein minerals deposited by circulating waters, are called *friction breccias*. Thus it may be seen that the angular fragments which give a "conglomeratic" appearance to the rock may arise in a variety of ways. The character of the cementing material, or matrix, in which the fragments are embedded, and the field relations usually serve to indicate the origin of the breccia. In an intrusion breccia, for example, the matrix is igneous rock. Some volcanic breccias, however, do not have a recognizably igneous matrix. An association with volcanic flows, nevertheless, might suggest the volcanic origin, as would the coarser lava fragments of which it is composed.

### Sandstones

Most sand is a water deposit. In arid regions, widespread sands have been laid down by wind action. Volcanic eruptions, glacial action, mechanical and chemical weathering, and organisms produce sands. However, streams and wave action account for the bulk of the sand deposits. Sands resulting from rock disintegration may consist of a large variety of mineral species. The disintegration of a granite, for example, yields a quartz-feldspar sand with a minor amount of other constituents such as hornblende or the micas. A feldspathic sandstone of this origin is called an *arkose*. Sandstones derived from the consolidation of dirty or muddy sands are called *graywackes*. In these, which are perhaps the most abundant of the sandstone varieties, the sand grains, predominantly quartz and feldspar, are set into a matrix of finer-grained rock or mineral paste.

In sands that have resulted from decomposition, the more soluble constituents and those more susceptible to chemical weathering have been eliminated. During the course of long transportation, also, the minerals less resistant physically or chemically tend to be eliminated. Thus quartz is the most abundant constituent in these sands and in the sandstones which result from their consolidation. Because sediments and sedimentary rocks themselves are subject to

weathering and renewed transportation and deposition, the elimination of the weaker and less resistant minerals may be almost complete. A pure quartz sandstone thus suggests more than one cycle of sedimentation.

The grains of a sand may be rounded, partially rounded, or angular. Grains that have been carried considerable distances or subjected to long continued wear commonly show a marked degree of rounding, whereas sands that have resulted from disintegration, volcanic explosion, or glacial action are commonly angular. Water- and wind-borne sediments commonly show a degree of assortment. Grains of similar size or weight are selectively transported and segregated. The degree of assortment may be very high, as for example in many wind deposits or grains deposited on gently sloping sea floors. Stream deposits are commonly somewhat less well graded. Giacial deposits show the most marked heterogeneity because of marked fluctuations in the velocities of the glacial melt-waters. These characteristics of sands are also those of their consolidated counterparts, the sandstones.

***Consolidation of Sandstones.*** After they have been deposited, sands may be compacted and the fine material, particularly a clay content, may serve as a cementing agent Cement of this type is not always durable; it may slake down on wetting, permitting the rock to crumble. The common mineral cements, as in the conglomerates, are calcite, quartz, and iron oxides. If the sandstone is thoroughly cemented with silica, the matrix may be as strong as the individual sand grains; on breaking, the fracture passes indiscriminately through the grains and matrix. The sandstones thus thoroughly cemented with quartz are termed *orthoquartzite*. There are all degrees of cementation to be found, varying from virtually unconsolidated sands to the sedimentary quartzites just mentioned.

***Properties of Sandstone.*** Sandstone is a common and widely occurring sedimentary rock type. Used as dimension stone, color may be a selection factor, as well as its strength properties. Its porosity and permeability are significant in some sanitary engineering and

water supply problems, as well as in the construction trades. As a construction material, also, its durability must be considered.

*Color.* The color of sandstones varies from white, for the virtually pure quartz rock, to almost black for the ferro-magnesian stones. Commonly the lighter shades prevail in various tints of buff because of iron staining. Reds and browns, also due to iron staining, are very common. There is difference of opinion as to the significance of red color in sediments. Some geologists have maintained that a red coloration indicates an arid or semiarid environment of deposition. Others have held that a red coloration more frequently signifies a humid environment of deposition. In any event, the red coloration signifies oxidizing conditions.

*Crushing Strength.* The crushing strength of many commercial sandstones falls between 5000 and 13,000 pounds per square inch. This property depends on the nature and quantity of the cement. The sedimentary quartzites, for example, give crushing strengths far in excess of the range mentioned. On the other hand, a weakly cemented sandstone may have a crushing strength far below the average cited.

*Transverse Strength.* Not many data are available on the transverse strength of sandstones. The few values that have been recorded indicate moduli of rupture between 400 and 2500 pounds.

*Porosity and Permeability.* Sandstones are among the most porous of the consolidated rocks, although certain sedimentary quartzites may have less than 1 per cent pore space. Many commercially used sandstones have a range of porosity between 2 and 15 per cent. Depending upon the size and arrangement of the pore spaces, the sandstones show various degrees of permeability. Generally speaking, the sandstones are the most permeable of the consolidated rocks. The absorption of sandstones likewise depends upon the size and arrangement of the pore spaces, i.e., upon the degree of cementation. The range of absorption is about the same as that of the porosity. Table I of Appendix II shows the absorption values for a number of commercial sandstones. If the sandstone is in posi-

tion to drain freely, it is not particularly susceptible to frost damage due to the freezing of absorbed water. Under conditions of poor drainage, disruption by freezing may be excessive.

*Durability.* Sound sandstones are durable. The rock has a good fire resistance and, in this respect, is superior to most of the rock used as dimension stone. Fire and frost damage are both minimized by laying the sandstone blocks with the bedding planes horizontal. In some sandstones, iron carbonate or other iron mineral may be present and cause discoloration of the stone on oxidation. This is uncommon in sandstones, however, and the rock is not commonly subject to color change. A clay cement is deleterious, particularly if the rock is subject to wetting. Clay seams or thin clay beds are sources of danger and, if present, may lessen the life of the stone. A calcareous cement is, of course, subject to leaching by acids.

*Sandstone as Construction Material.* Sandstones are used in a good many different ways. In particular they are used for both inside and outside building, for trim, pillars, walls, and flagging; for bridge and dam construction; and for sea and retaining walls. The firmly cemented sandstones are used to a minor extent as crushed rock, and sandstone pebbles are prominent in some commercial gravels.

## Argillaceous Rocks

The argillaceous rocks, variously called *mudstone, claystone,* and *shale* are among the most abundant of sedimentary rocks. Mineralogically, they are made up of a variety of components. The dominant constituents of most claystones, however, are the clay minerals, sericite mica, and quartz. Clays are of various origins. It has been shown that clay is a product of chemical weathering and as such may accumulate as a layer of residual soil or undergo transportation. Clay is also produced by mechanical grinding or abrasion, as for example, by glaciers. Commonly, the argillaceous rocks result from the compaction and consolidation of clays and silts that have been transported and have been deposited in seas, lakes, swamps, and along stream valleys.

***Consolidation of Argillaceous Rocks.*** There are all gradations between the clays and their consolidated equivalents, the claystones or shales. The distinction between clay and claystone is not always easy to make. Twenhofel [1] distinguishes as shales those which when soaked retain coherence, and as clays those which slake and fall apart on wetting. Compaction and expulsion of water attend the consolidation of clays. It has already been pointed out that sericite mica forms during the process of consolidation. In the consolidation of clays, owing to their fineness of grain and impervious character, cementation by mineral matter brought in by percolating waters is of small account. The colloids present, together with the forces of surface attraction, serve to bind the clay into coherent masses, assisted by the crystallization of quartz and mica.

***Properties and Uses.*** The color of the argillaceous rocks varies from light gray to black. The shades of gray are probably due to organic material. Both red and green shales are also common. The red shades are due to unreduced ferric oxides, and the greens to minute mineral particles of a green color, as for example the chlorites.

The claystones, because they are characteristically soft and weak are not suited to most construction purposes. Mead [2] makes a distinction between *compaction* shales and *cementation* shales. The compaction shales lose strength when wet and are subject to plastic deformation. Under load they are subject to failure by flow. The cemented shales have a strength comparable to that of concrete but have a relatively high elasticity. Claystones underlying the sites of heavy structures should be tested in both wet and dry condition; and it should be borne in mind also that rapid run-down tests may give misleading results. Claystone has a relatively limited use. It serves as a raw material for the ceramic industry in some places; and the pulverized rock is also used as one of the ingredients in some Portland cements.

[1] Twenhofel, W. H., *Treatise on Sedimentation*, 1932, p. 241.
[2] Mead, W. J., "Geology of Dam Sites," *Civil Engineering*, Vol. 7, 1937, p. 392.

### Carbonate Rocks

The carbonate rocks are chiefly the products of marine or fresh-water sedimentation. They are predominantly chemical sediments either formed by the metabolic processes of organisms or precipitated inorganically. Mineralogically, the carbonate rocks are comparatively simple. There are two main varieties: the limestones composed chiefly of calcite, and the dolomites composed chiefly of the mineral dolomite. As in the other groups of sediments, gradations occur which give rise to compound names, for example argillaceous limestone, silty or arenaceous limestone, magnesian limestone, and others. The classification diagram (Fig. 7-1) shows the principal gradations and suggests limits for several subvarieties of impure limestone.

***Varieties.*** Limestones have several different modes of origin, and display many textural variations. Even within limestones of the same origin, a great range of textures is displayed. In some the texture is so dense that no visible grains are to be seen and the rock superficially resembles a felsite or basalt. On the other hand, it may be coarsely granular with the calcite or dolomite readily recognizable. In many limestones fragments of seashells of various kinds may be present. In some limestones, rounded particles known as *oolites* or *pisolites* are abundant. Oolites and pisolites are concretionary structures, generally built of concentric layers deposited about a nucleus. Oolites are about the size of a pinhead, while pisolites average about the size of a pea. Some rock types other than the carbonate rocks show oolitic or pisolitic composition, as for example certain iron and aluminum ores. Typically, however, this character is best displayed in limestone.

***Organic Limestones.*** Limestones may be developed through the accumulation of the hard parts of many organisms, particularly the marine invertebrates which use calcium carbonate in manufacturing protective and supporting structures. Shell sand and shell banks, as well as coral reefs and coralline sands, are examples of present-day carbonate deposits that are familiar to all.

Precipitation of calcium carbonate is also brought about by the

action of subaqueous green plants which remove carbon dioxide from the water, changing the soluble calcium bicarbonate to insoluble calcium carbonate. Both algae and bacteria are plants that have varieties which cause the precipitation of calcium carbonate. Accumulation of calcareous muds, silts, or clays are sometimes called *marl.*

***Inorganic Limestones.*** Inorganic precipitation of calcium carbonate is brought about in a number of ways. Any disturbance or agitation which lowers the carbon dioxide content of the water may cause precipitation. Release of pressure or warming of the water may also reduce the carbon dioxide content, giving rise to precipitation of the carbonate. Evaporation may have the same result.

***Subvarieties.*** From the foregoing summary of the two principal types, it may be seen that a considerable variety of environments gives rise to limestone deposits. These environments include the shallow water marine zones, caves, springs, lakes, and the dry plains. Furthermore, clastic limestones may be formed at any place where pre-existing limestones are being reworked. Many names have been applied to lime deposits. A few of the more common are:

*Chalk.* An accumulation of powdery calcium carbonate. It is probably of both organic and inorganic origin.

*Caliche.* A crusty deposit of calcium carbonate and sometimes other substances, due to the evaporation of soil waters at the surface of the ground in dry regions.

*Coquina.* A limestone made up largely of shells and shell fragments.

*Lithographic Limestone.* A very uniform, dense-textured limestone used in lithographic work.

*Mexican Onyx.* A layered deposit formed on the floors and walls of caves, and less commonly about springs.

*Stalactites* and *Stalagmites.* Waters leaking through the roofs of caves may deposit calcium carbonate in the form of stone icicles pendent from the roof or build up columns from the floor where the dripping water strikes. The pendent forms are called *stalactites;* columns rising from the floors are called *stalagmites.*

*Travertine.* Compact and banded deposits, particularly about springs.

*Tufa* or *Calcareous Tufa*. Also a spring deposit, being very porous and spongy in character. Tufas are also deposited in salt lakes and playas of dry regions.

The discussion so far has dealt chiefly with the limestones. There are a number of other varieties of carbonate rocks, for example the magnesium and iron carbonates, and others less extensively developed. Aside from the limestones, however, magnesium limestones and dolomites are the most widespread and important members of the carbonate group. *Dolomites* are rocks made up wholly or in large part of the mineral *dolomite*, which is the double carbonate of calcium and magnesium—$CaMg(CO_3)_2$. There is a tendency among geologists at present to substitute the term *dolostone* for the rock type, thus restricting the term *dolomite* to the mineral species. Dolomite is formed in a number of different ways. Replacement of part of the calcium of limestones by magnesuim is the most important and widespread process involved in the formation of dolostone. The replacement is not always complete, and there are many gradations between limestone and dolostone. The replacement of calcium by magnesium probably occurs in most instances in the early stages of consolidation. Most dolostone appears to have been formed in shallow marine waters under reducing conditions.

***Physical Properties of the Carbonate Rocks.*** The range of values for the physical properties of the individual carbonate rock types is large, as might be anticipated from the variety of types just listed. Color, strength, porosity, and permeability are among the most significant.

*Color.* Limestones vary in color from almost pure white through varying shades of gray to black. The darker shades are, in most instances, caused by carbonaceous material. The presence of iron oxides gives rise to buffs, browns, and reds. The dolostones are commonly light in color. They often carry ferrous iron compounds which oxidize, tinting the rock shades of buff and brown.

*Strength.* The strength of most limestones and dolostones used for building purposes is sufficient to give a reasonable safety factor. As in the other types of rocks, the strength properties vary with the

degree of consolidation. Because the carbonate rocks are readily recrystallized, the individual calcite and dolomite crystals are firmly interlocked, and the cohesion of most limestones is in a large measure due to recrystallization. Appendix II shows the strength properties of a number of limestones and dolostones. Crushing strength ranges between 10,000 and 15,000 pounds per square inch for many commercially used limestones. Fewer data are available on transverse and shearing strengths.

*Porosity and Permeability.* The intergranular porosity of limestone and dolostone is generally low, and the absorption of sound types is correspondingly small. Because the carbonate rocks are relatively soluble, however, solution cavities may be abundant, and many of the joints are enlarged by solution. In fact, the presence of solution cavities and hence ready permeability should always be suspected until contrary evidence is secured.

*Uses.* The carbonate rocks, particularly the limestones, have a very wide use in modern industry. The diversity of their application and the volume of demand are probably exceeded by no other group of consolidated rocks except the coals. The largest single use is as crushed stone. More than 65 million tons of limestone are crushed annually. The next largest use is as a fluxing stone in metallurgical fields. Limestone is one of the leading dimension stones, being utilized both for internal and external work. The chief ingredient in the manufacture of cement is limestone. Commercial lime is derived from the burning of limestone, and land lime is pulverized raw limestone. Among the many other uses might be mentioned manufacture of rock wool, glass manufacture, and sugar refining. Dolostone also has a wide use, as crushed stone, in the manufacture of paper, in the production of magnesium land lime, and as a source for metallic magnesium, as well as many others.

## Siliceous Sediments

Siliceous sediments are those composed chiefly of silica. Excluded from this group, however, are the siliceous sandstones and quartzites. The texture of the siliceous sediments is characteristi-

cally dense. They are, for the most part, chemical precipitates or replacement bodies. The most common occurrence of these sediments is as nodules, lenses, or beds in association with limestones and shales. Fig. 7-2 illustrates a typical example of nodular or lens occurrence.

FIG. 7-2. Chert lenses in limestone near Columbia, Missouri.

Ground waters carrying silica may effect a bit-by-bit replacement in such a way that even the most delicate structures may be retained. A common example of siliceous replacement, familiar to most, is petrified wood. Rock, as well as wood, may be replaced; limestone and dolostone, for example, are especially susceptible to silicification. Replacement by silica may be localized by some particular stratum of rock, by a fault or fracture zone, or along the margin of an igneous intrusion. It is probable, likewise, that some silicification takes place beneath the seas in the early stages of lithification. Some siliceous sediments are of organic origin, resulting from the accumulation of siliceous remains of certain organisms.

***Varieties.*** The siliceous sediments, like the carbonate rocks, display a great variety. Only the most abundant types—chert, jasper, and flint—are included in this discussion.

*Chert.* Chert is a dense-textured, white to buff colored rock, which occurs as lenses or nodules or as beds usually associated with

limestone. Typically it shows a conchoidal fracture. The lenses are commonly confined roughly to a single bed or distributed parallel with the bedding of limestones. The lenses vary in size from a few inches to a few feet in thickness, and from a few feet to twenty or thirty feet in horizontal dimensions. Massive beds of considerable proportions, however, are not uncommon.

*Jasper and Flint.* Jasper and flint are similar in composition and occurrence to the cherts. They, like the cherts, are dense in texture and commonly break with conchoidal fracture. The jaspers are colored red; the flints dark gray to black. Jasper is commonly associated with ferruginous rocks; flints are abundant in chalk beds.

*Properties.* Chert and its variations, jasper and flint, are dense, hard, and somewhat brittle. Fresh sound chert makes good gravel or concrete aggregate. The experience of engineers in a number of states, however, has shown that many chert fragments embedded in the surfaces of concrete pavements tend to shatter and pop out, leaving pits in the pavement. The explanation for this seems to be that some chert is honeycombed where associated calcite has weathered out, rendering the chert susceptible to frost action. This may be enhanced also by the development of incipient cracks in crushing, owing to the brittleness of chert.

## Carbonaceous Sediments

Many accumulations of vegetable matter are found throughout the recently glaciated regions in depressions and swamps. Similar accumulations are being formed in swamps in other parts of the world as well. In the stagnant water of swamps, the decomposition of vegetable matter produces substances of preservative nature in that they are poisonous to the microbes of decay. The accumulated and partially decomposed vegetable matter, pickled in its own juice, is termed *peat.* Often, an admixture of inorganic material, principally fine mud or clay, is found with the peat. This mixture is the *muck* of engineering practice. Not uncommonly, peat deposits margin lakes with low banks. Because of the high water content, peat and muck are highly compactible. It has been suggested that 1 foot

of peat at the surface may compact to a thickness of $1\frac{1}{8}$ inches in a deep bog.[3]

Biochemical alteration of peat into humus, probably largely by the action of anaerobic bacteria and continued compaction, gives rise to the so-called brown coal, or *lignite*. Further compaction with the attendant chemical changes transforms the lignites into the higher rank coals, bituminous and anthracite. Carbon-rich mucks and clays are consolidated into black shales, which on metamorphism become black slates and graphitic schists.

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CHAPTER VIII

# METAMORPHISM AND THE METAMORPHIC ROCKS

METAMORPHISM IS A GENERAL OR BROAD TERM WHICH includes all rock alteration. Commonly, however, a more restricted usage is followed, whereby metamorphism includes only processes which remake the rock into one of equal or greater coherence and crystallinity. The agents that produce metamorphism are heat, stress, and solutions. The dominant process is recrystallization.

## PROCESSES OF METAMORPHISM

Four processes may be distinguished in an analysis of metamorphism: granulation, plastic deformation, recrystallization, and metasomatism. Although for convenience these are considered separately, in nature the processes overlap and frequently have been concurrently effective in the production of metamorphic rocks.

***Granulation.*** Breccias formed by the crushing of rock along faults have already been noted. In deeply buried masses, however, crushing may be pervasive, and brecciation may amount to pulverization. Breaking of the minerals is generally initiated at their margins; projections are broken off, and the margins crushed. Ultimately, the whole mass may be pulverized, forming a *micro-breccia* or *mylonite*. This crushing, called *granulation,* takes place without development of visible openings and without loss of coherence. Depth of burial, confinement, and rapid stress application consequently are implied.

***Plastic Deformation.*** Plastic deformation is nonelastic change

of shape or form of a solid without conspicuous fracture. If any crystal is sufficiently stressed, for example, it does not return to its original form on removal of the stress, but remains at least partly deformed. In individual crystals this strain is most commonly accomplished by slip or gliding along internal crystallographic planes or by twinning. In some metals it has been shown that the slip bands are on the order of one micron apart. In the plastic deformation of crystalline rocks, flexible minerals, such as mica, may be bent.

***Recrystallization.*** Recrystallization is the regrouping of the elements into new crystals. Atomic rearrangement may form either new minerals or new crystals of minerals formerly present. Just how this rearrangement takes place is not fully understood, although recent work has shed much light on the matter. Plastic deformation and granulation have been described as processes of metamorphism. During granulation heat is produced, which locally may be even sufficient to partially melt the rock. During granulation, also, individual crystals are plastically deformed. If a crystal is stressed to the point of plastic deformation (slip on gliding planes), and the deforming stress removed, there is a residual internal stress produced by the deformation, due to bending or distortion of the lattice adjacent to the gliding planes. This stored energy of deformation —strain energy—is the "driving force" for recrystallization of stressed materials. As stated by Buerger and Washken: [1] "If a mineral which is so deformed is subjected to conditions under which a transfer of its matter is possible, it will distill, or dissolve, so that its matter comes to be added to a strain-free crystal or crystals. To have this transfer take place, it is only necessary to heat the strained mineral until its vapor pressure gives rise to an appreciable transfer of material from strained to unstrained crystals. Alternatively, the transfer may be accomplished by placing the strained mineral in a fluid in which it is slightly soluble. Either means provides the vehicle for transfer of matter from strained to unstrained crystal, and hence induces recrystallization." It may be noted, in addition, that the

[1] Buerger, M. J., and Washken, E., "Metamorphism of Minerals," *Amer. Mineralogist*, Vol. 32, 1947, p. 297.

solubility of minerals is greatest at points of maximum stress. At these points mineral substance may pass into solution to be redeposited in positions of less stress concentration. Thus, a very small amount of fluid in many rocks may be a highly effective agent of recrystallization, since even in minute quantity it may form a medium through which atoms may move from one position to another. In the absence of solvents, recrystallization takes place only if the critical temperature for the considered mineral is reached. The critical temperature decreases, however, with an increase of deformation. Dry recrystallization is probably less common in rock metamorphism, however, than in transformations of metals.

Certain minerals characteristically developed in a stress environment, mica for example, have compositional water in their formulae. Hence, those rocks which contain an abundance of secondary mica or other hydrated minerals are probably the results of metamorphism of weathered or altered rock, for fresh igneous rocks are nearly anhydrous. Hydrated minerals, such as kaolinite, may supply a part of the necessary water.

From the foregoing discussion of recrystallization, it can be seen that precedent or contemporaneous deformation is an aid to recrystallization because both strain energy and heat are generated. Another process of recrystallization, however, should be mentioned. Many powdered solids, pressed together and heated at elevated temperatures, although well below the fusion or evaporation points, sinter into firm masses. The driving force is the surface energy, which is proportionately larger, the smaller the initial size of the particles.

In the recrystallization of rocks, it appears probable that both strain energy and free surface energy are important factors and, in conjunction with elevated temperatures and the presence of water, bring about the transformation. Recrystallization is a slow, piecemeal process. The rock is reconstituted, and often made stronger and more compact, by its failure to withstand overpowering stresses.

***Metasomatism.*** *Metasomatism* is defined as the essentially simultaneous solution and precipitation of mineral matter at a common

point or place in the rock. It is a volume for volume replacement of one substance by another. A product of metasomatism familiar to all is petrified wood. Examples of mineral metasomatism are abundant and are of particular importance in the study of ore deposits. Inasmuch as the replacement is a volume for volume substitution, even perhaps in atomic or ionic units, the preservation of structures and textures may be perfect, as illustrated by the delicate wood cell structures frequently exhibited by petrified wood. Whereas recrystallization may take place in essentially closed systems, replacement implies an open system with introduction and removal of material which may locally involve enormous amounts.

Replacements in the surficial zones of weathering are effected through the agency of subsurface water. In the deeper zones, however, the common source of mineralizing or replacing solutions is the crystallizing magma of an intrusion. Any avenues of ready percolation, as fracture planes, permeable beds, solution channels, foliation planes, or cleavage cracks, serve as lines of entrance and advance of the gaseous or watery solutions which are the agents of transfer, solution, and precipitation. Much of the material removed may ultimately find its way into the ground water system.

If the magmatic emanations are gaseous, the alterations produced are *pneumatolytic;* if they are aqueous, the metamorphism is called *hydrothermal.* Aside from the ore minerals, those commonly introduced metasomatically are tourmaline, fluorite and the fluorine-bearing micas, chlorine-bearing apatite and scapolite, pyrite, garnet, and soda and potash feldspars. These minerals indicate that the emanations commonly contain fluorine, boron, chlorides, iron, soda, potash, and silica. All rocks are susceptible to replacement. The carbonate rocks are the most readily replaced, and the quartz rocks, although not immune to the process, are the least susceptible.

### Types of Metamorphism

Two general types of metamorphism are distinguishable: contact metamorphism and dynamic metamorphism. The first, *contact metamorphism,* occurs in association with igneous invasions; and the

second, *dynamic metamorphism,* occurs in association with major earth movements and deformation. Over wide areas where intrusion and mountain-making have been effective, metamorphism may be general; hence the expression *regional metamorphism* is frequently used by many geologists.

An elevation of temperature with increasing depth is universally noted, although values for the increase are variable in the several localities where measurements have been made. The average increase in temperature with depth is roughly 1° C. per 100 feet. Temperature data are available for only a small fraction of the earth's radius, however, and any extrapolation of the thermal gradient curve to great depth is at best inferential. In the deeper zones, nevertheless, it is safe to assume temperatures high above those of most parts of the outer zones. It may be estimated, for example, that at depths of some 7 miles the temperatures approach the critical temperature of water (364°). Based on the concept of temperature increase with depth, some geologists recognize thermal depth zones of metamorphism. The common cause for elevated temperature in the outer segments of the earth, however, is the movement of magma from within. Hence the most commonly observed metamorphic changes due to high temperatures are those associated with igneous intrusions. The heat effects are localized about the intrusion, forming a metamorphic aureole, which seldom extends as much as 2000 feet from the contact and is commonly of much lesser extent. Solutions may or may not enter the contact rocks from the intrusion. Although the intrusion may set up shearing stresses in the contact rocks, it appears that more commonly, perhaps, the stresses are balanced, or hydrostatic. Dynamic metamorphism on the other hand implies rock flowage or deformation under the influence of differential or shearing stresses. The temperatures may be either high or comparatively moderate.

***Contact Metamorphism.*** Contact metamorphism may be the result of temperature increases acting under hydrostatic pressures, with little if any introduction of material from the magma. Contact metamorphism may also take place with the introduction of mag-

matic constituents on wholesale scale. The explanation of the two different types is probably found in the distinction between "dry" and "wet" magmas. The dry magmas are poor in volatile constituents such as $H_2O$, Cl, B, F, and others; whereas wet magmas are relatively rich in those fugitive constituents. The contact effects of the dry magmas may be designated as *thermal metamorphism*: the contact effects of the wet magmas may be called *additive contact metamorphism*.

*Thermal Metamorphism*. Heat effects alone produce baking and hardening, dehydration, and frequently induce some degree of recrystallization, with a resultant coarsening of texture.

The efficacy of some solvent medium in the rock to promote recrystallization has already been indicated. Interstitial or compositional water, as well as water contributed from the magma, serves as an agent of recrystallization. Most magmas crystallize at temperatures of less than 1000° C. and some below 600° C. There is, consequently, little evidence of pure melting along igneous contacts. Whatever the temperatures of magmas may have been at great depths, by the time they have reached the levels of final consolidation they are unable to melt the minerals of the walls and roof rocks.

Not infrequently a zonal gradation of metamorphic effects is to be noted about an intrusion. This is especially true if the country rock is argillaceous or calcareous. At some distance out from the intrusion chlorite may appear in the country rock, the chlorite zone. Nearer the intrusion biotite may appear, indicating a higher grade, or higher temperature metamorphism; still closer to the contacts higher temperature minerals, such as sillimanite, are developed. The mineralogical transformations are usually accompanied by an increase in grain size so that the rocks adjacent to the contact itself may be coarsely crystalline and altogether different in aspect from those of the original rock.

High pressure of the hydrostatic or balanced type favors diminution of volume. Hence during recrystallization, recombination of many of the elements may form denser minerals. One result of recrystallization, the formation of metacrysts, is noteworthy because

these crystals of metamorphic origin are frequently mistaken for the phenocrysts of a porphyritic igneous rock. *Metacrysts* are metamorphic minerals occurring as crystals larger in size than the grains which surround them (Fig. 8-1). Unlike phenocrysts which develop early in the consolidation of the igneous porphyries, metacrysts are late crystallizations in solid rock. They are apparently a response to the demand of the pressure for diminution of volume. Most metacrysts

FIG. 8-1. Metacrysts in metamorphic rock.

are anhydrous silicates of high specific gravity. Common minerals occurring as metacrysts are garnet, andalusite, staurolite, and feldspar. Metacrysts are not limited to contact metamorphic rocks. They are also found in dynamically metamorphosed rocks.

*Additive Metamorphism.* About many igneous intrusions there have been large-scale transfers of igneous material into the wall and roof rocks. The contact rocks are thus made up of materials of mixed origins and consist of a host and its guests. These mixed rocks

are called *migmatites*. Most migmatites have a somewhat granitic composition, and many have metacrysts. The common mineral constituents are feldspar, quartz, mica, hornblende, garnet, cordierite, sillimanite, epidote, calcite, and frequently sulfides.

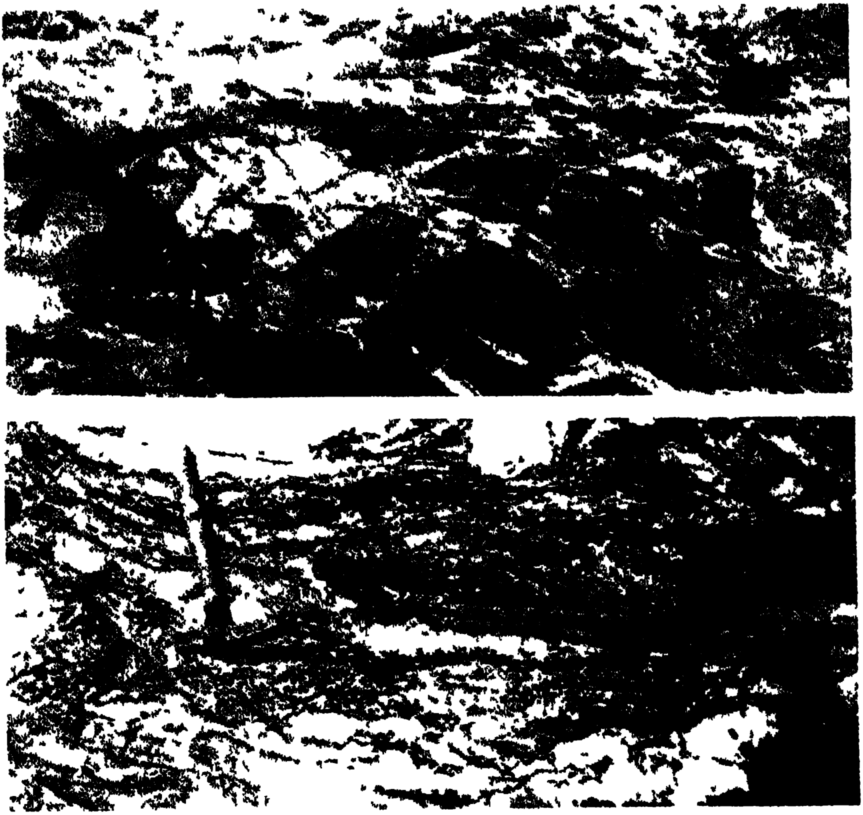

FIG 8-2. *Above:* Migmatite formed by fracture controlled injection *Below* Migmatite formed by *lit par lit* injection

In many contact zones, magmatic solutions are forced into the country rock along the paths of least resistance If the country rock is jointed, the joints are occupied by a network of ramifying dikes, as shown in Fig. 8-2A. If the host rock is foliated or bedded, thin sills may be forced between the layers of bedding or foliation in countless numbers, giving rise to the so-called *lit-par-lit* structure of the type shown in Fig. 8-2B. The solutions invading the host rock may be

normal magmatic solutions, giving rise to dikes and sills; or they may be quite watery, thinly fluid, or even gaseous, giving rise to veins. In the latter case, extensive alteration and metasomatism of the rock adjacent to the vein may take place.

Locally, unaltered sediments when traced along the strike show changes in composition, becoming progressively more granitic. More and more material appears that was lacking in the unaltered sediment, and it might be assumed that introduction has taken place. The sedimentary structures, bedding and folds, however, may be preserved, marked out by banded contrasts in mineralogy of the igneous-looking rock. The substitution of igneous material in these instances must have been passively achieved, by metasomatic replacement pervasive throughout the mass. The process is frequently called *granitization* Some geologists hold that the change does not mean large-scale introduction and removal of material, but rather that most of the alteration is due to recrystallization without much change of bulk composition.

The problems of igneous contacts, metasomatism, vein formation, and rock alteration are of high importance in mining geology. It is only necessary to point out that many, if not most, ore deposits are related to igneous activity. A study of migmatites leads naturally to the consideration of some of the major problems of geology which are beyond the scope of this volume, as for example the origin of granites and other igneous rocks.

***Dynamic Metamorphism.*** Metamorphism due to plastic solid flow of rocks is called *dynamic metamorphism.* Rock flowage is the yielding of the mass, change in shape, without conspicuous fracture. Soft unconsolidated sediments, as clay for example, fail plastically by intergranular rearrangement. In the plastic deformation of solid rocks, however, intragranular adjustment and recrystallization induced by the strain are of much greater significance.

***Foliation.*** It was noted in the discussion of contact metamorphism that pressures were essentially hydrostatic. In dynamic metamorphism unbalanced stresses are in control. The rock mass undergoes elongations and shortenings. Because this is true, there is a

directional control for the orientation of the new minerals adapted to the stress environment which are formed by the rearrangement of the elements comprised in the minerals of the rock prior to alteration. Some minerals, like the micas, amphiboles, and chlorites, are particularly influenced by this directional control and crystallize in positions subparallel to each other and to the plane of rock elongation. This principle is illustrated in Fig. 8-3, which shows a cross-section of a unit sphere of rock, deformed into an ellipsoid. The long axis of the ellipsoid, designated $A$, is the direction of greatest elongation. The short axis, designated $C$, is the axis of greatest shortening. The intermediate axis, $B$, is normal to the plane of the paper. It is obvious that the plane of maximum elongation is the plane including the $A$ and $B$ axes. Mica plates have been oriented during growth so that they lie with their cleavage planes parallel to the elongation plane of the rock, and perpendicular to the axis of greatest shortening. This subparallel arrangement of platy or needle-like minerals brought about by recrystallization during rock flow is called *foliation*. The foliation planes are comparable to the leaves of a folio or book, hence the name.

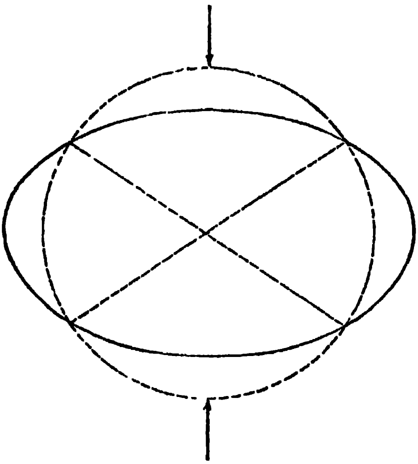

FIG. 8-3 Cross section of a sphere deformed into an ellipsoid.

In part, foliation is doubtless brought about by reorientation of the grains already present in the unmetamorphosed rock. More important, however, is the development of the relatively few platy and elongate minerals characteristic of the foliates at the expense of the minerals in the unaltered rock. This is clearly demonstrated by the great increase in amount of mica, amphibole, or chlorite in the metamorphosed rocks as compared with their unmetamorphosed equivalents. Foliation is especially common in folded sedimentary rocks.

It also develops as a result of rock flow attending faulting or shearing, intrusion, or as a result of superincumbent load, and it is found therefore in rocks of diverse origin.

The necessary condition for the development of foliation in metamorphic rock appears to be rock flow, which gives directional control to mineral growth during recrystallization. Foliation displays all degrees of perfection. If the rock has a favorable chemical composition, the foliation may be very perfect, as in slates; if the chemical composition permits only a limited development of minerals of the platy or needle-like habit, foliation is crude. The factors of temperature, stress, rate of stress application, load, and solutions present are certainly important, but difficult to evaluate. Elevated temperatures, deep burial, shearing stresses, sufficient water, and a favorable bulk chemical composition are requisites for foliation development.

*Massive Structure.* Not all dynamically metamorphosed rocks have foliation. Some minerals, notably quartz, calcite, and feldspar, which are common in the metamorphic rocks, do not give rise to a foliated structure because of their crystal habits. Rocks composed dominantly of these minerals, consequently have a massive structure, with no preferred or easy direction of "splitability." It is noteworthy, however, that careful microscopic examination of many of the massive metamorphic rocks produced by rock flow reveals a degree, at least, of orientation not megascopically observable. Certain marbles, for example, cut with careful regard for this structure may be translucent in thicknesses up to half an inch or more. Cut in any other direction, they are opaque in thicknesses of a minute fraction of an inch.

The dynamically metamorphosed rocks often display metacrysts. These are apparently late in the history of recrystallization; following relief of the deforming stresses by rock flow, hydrostatic pressures may prevail, favoring metacryst growth. Alternatively, some metacrysts are probably metasomatic replacements caused by solutions entering the rock after metamorphism.

## Products of Metamorphism

Metamorphic rocks, with minor exceptions, are crystalline. That means that in contrast with many sediments, the metamorphics are almost exclusively composed of interlocking crystals and not bonded together with cements. In this respect, they resemble the igneous rocks. They are frequently banded or foliated. Some igneous rocks also are banded and some have a crude foliation. These structures in the metamorphic rocks, however, are better defined, more conspicuous, more regular, and more frequent. Some metamorphic rocks are massive. The massive metamorphics are harder and more crystalline than the massive sediments and have a mineral composition different from that of the massive igneous rocks. Some minerals, such as garnet, staurolite, sillimanite, graphite, and others, are good indicators of metamorphism, as are also mica or chlorite in great abundance. The principal difficulty, after some acquaintance with metamorphic rocks, is not to recognize their metamorphic character, but to determine the nature of their unmetamorphosed predecessors and the processes that have produced them.

***Classification.*** Along many contacts, dynamic metamorphism has worked with or followed contact action; and in many regions of folding and deformation, contact or thermal metamorphism has played a role complementary to dynamic metamorphism. In terms of products, therefore, it is not always possible to refer this rock to contact action, and that one to dynamic action. Further, the same rock types may be produced by the two different classes of cause. The classification of metamorphic rocks, therefore, is descriptive rather than genetic. The scheme of classification (Table 8.1) is based on structure, mineralogy, and grain size. The scheme is by no means complete but includes the commonly encountered types.

***The Massive Rocks.*** The three principal types of massive metamorphic rocks are *quartzite, marble,* and *hornfels.* Of these, quartzite and marble may be produced by either contact or dynamic metamorphism. Hornfels is always a product of contact metamorphism.

*Quartzite.* Quartzites are metamorphic rocks of sedimentary

TABLE 8.1. COMMON METAMORPHIC ROCKS

| Texture | Foliated | Nonfoliated |
| --- | --- | --- |
| Dense | Slate | Hornfels |
| Fine | Phyllite (Mica visible as silky sheen) | Hornfels<br>Quartzite (Dominantly quartz) |
| Medium to coarse | Schist (commonly mica, chlorite, or hornblende give the foliation) | Marble (Dominantly calcite or dolomite) |
| | Gneiss, (Foliation often poor, some without foliation. Feldspar, mica, hornblende, quartz common minerals.) | |

origin composed largely or wholly of quartz. They are derived from quartz sandstones and siltstones and differ from them in their crystallinity and strength.

Quartzites are the results of recrystallization. Both thermal and dynamic metamorphism produce them, and it is generally impossible to determine from the hand specimen which has produced the rock. A third type of origin for quartzites should be mentioned. In the course of cementation by silica, quartz sandstones or siltstones may become so completely cemented with quartz that porosity is reduced to practically zero. The crystalline quartz precipitated as cement between quartz fragments of the sediment is as strong as the grains it crystallized against. The rock thus becomes a real quartzite. (Cementation of sediments, although commonly not treated as such, is actually a constructive metamorphic process.)

The color of quartzites varies from pure white to various shades of pink and red due to iron oxide tints. Shades of gray also are common. The texture is usually fine or dense. Quartz is the dominant mineral constituent and frequently makes up 98 per cent or more of the rock. Many sandstones and siltstones, however, are not pure quartz. Admixed clays and other minerals of the sediments on metamorphism give rise to a variety of minor minerals in quartzites which

may be used in naming the rock. Micaceous quartzites, for example, are locally very abundant.

Quartzites are readily identified by their hardness and toughness, quartz composition, and occurrence as beds in a sedimentary sequence. The light-colored quartzites resemble some felsites or aplites. The darker-colored quartzites may be confused with diabases. The "quartzy" luster, after a little practice, usually serves to distinguish them. The recognition of phenocrysts or of a high proportion of feldspar indicates the rock is igneous. In the field, the mode of occurrence aids in classifying the rock.

Quartzite is a strong, wear-resistant rock. A summary of its strength properties is given in Appendix II. Quartzite makes an excellent crushed stone for any engineering use. The dark gray quartzites are often referred to by engineers as "trap" rock. Quartzite cubes are used in some ball mills, and some quartzite is used as a silica source in the manufacture of glass. The stone is difficult to work because of its hardness and therefore is little used as shaped or cut stone.

*Marble.* Marbles are metamorphosed carbonate rocks, derived from limestones and dolomites. Contact and dynamic metamorphism both produce marbles, and as with quartzites the distinction as to which process produced the rock is not commonly possible in the hand specimen.

The color of marbles is variable, although if the rock is pure calcite or dolomite marble it is generally white. Various impurities give rise to various shades, some of which are very attractive and add value to the stone. Greens, pinks, and buffs are common shades, and frequently black streaks are present. Green marble (verde antique) is colored by serpentine; diopside is another green mineral found in some marbles. The pink and buff colors are due to iron, and the dark gray and black colors, generally in streaks, are due to organic matter of the limestones which have crystallized to graphite. Biotite or other dark minerals may be present. In addition to the minerals just mentioned, actinolite and tremolite are common. Quartz, micas, and other minerals may be present in minor amounts, depending on

the purity and composition of the parent limestone. The presence of hard minerals in marble is injurious since it makes polishing more difficult. It is noteworthy that metamorphism brightens and clarifies the limestone colors. The texture of marbles is usually very uniform. It ranges from fine to coarse, depending upon the original texture of the limestone and the severity of metamorphism.

Marbles are readily distinguished by their dominantly calcite or dolomite composition, uniform texture, and occurrence. Dolomite marbles are slightly harder than calcite marbles and require powdering to effervesce in cold dilute acids.

The strength properties of marbles are given in Appendix II. The principal uses of marble are as cut stone for building and ornamental or decorative use. Floor blocks, walls, columns, stairways, and counters are illustrative examples. Much marble is also used as monumental stone. Marble is used as a source for lime, and it is pulverized for whiting. Dolomite is also an ore of magnesium metal.

*Hornfels.* Hornfels is a fine grained to dense, massive, contact rock. The most commonly recognized type is the cherty or felsitic looking dense hornfels that results from the baking and silicification of shales at igneous contacts. However, almost any rock type may crystallize to massive sugary-textured types, and the mineralogical varieties of hornfels are, consequently, very diverse. Hornfelses are rocks that have undergone thorough recrystallization under hydrostatic pressures rather than under shearing stresses so that the minerals have no preferred orientation. The rock, therefore, is tough and strong. Hornfels is not much used, although some makes excellent crushed stone. Most hornfels is called "trap" rock by contractors and engineers. For practical purposes, many hornfelses can be satisfactorily classified as impure quartzites.

***The Foliated Rocks.*** Metamorphic foliation, as already explained, is parallelism of unequidimensional minerals. More or less synonymous with foliation are the terms *flow cleavage, schistosity,* and ***slaty cleavage.*** The common foliated rock types in order of increasing grain size are: *slate, phyllite, schist,* and *gneiss.* In a general

way, this arrangement also corresponds to increasing intensity of metamorphism.

*Slate.* Slate is a dense metamorphic rock, with a strongly developed foliation. The rock cleavage, or "splitability," is therefore excellent and is the outstanding characteristic of slates.

The majority of slates are the result of dynamic metamorphism of argillaceous sediments. Altered basic igneous rocks of the fine textured types, however, have locally been altered to slates. In previous discussion it was noted that the clay minerals are principally hydrous aluminum silicates. It was further noted that, as these are formed during the weathering processes, they tend to absorb or adsorb potash. The clays and shales, therefore, contain the ingredients of mica and quartz. Under conditions of rock flowage at proper depth, shales recrystallize, with mica and quartz as the dominant constituents. Inasmuch as differential movement controls the orientation of crystals during recrystallization, the microscopic particles of mica are oriented parallel to a common plane (the plane of maximum elongation) and give the rock a pronounced slaty cleavage or foliation. After slaty cleavage has been developed, further deformation may crumple or fold the cleavage planes.

The color of slates varies from iron-tinted reds through various shades of gray and green. The gray shades are due to carbonaceous matter, the greens to chloritic micas. The texture of slates is very fine or dense, and the foliation is good to perfect. The higher quality slates can be split to thicknesses of a small fraction of an inch. Slates are composed principally of quartz and secondary mica (sericite), with pyrite, calcite, chlorite, and biotite common. If calcite is abundant, the term *calcareous slate* is used.

Slate is used widely in the electrical industries as switchboards, bases, and various turned and shaped parts. In the construction trades, slate is used for shingles, floors, mantels, and in a variety of other ways. Roofing granules and slate-flour fillers are other uses, and the list could be greatly extended.

*Phyllite.* Phyllites are strongly foliated metamorphic rocks similar to the slates but of slightly coarser texture. Whereas in the slates

discernment of mica requires magnification, in the phyllites tiny glistening flakes of mica can be seen on close observation. The rock, therefore, is more lustrous than slate and commonly somewhat crumpled or warped, so that it does not split into plane surfaces as do the slates. The mineralogy of phyllites is similar to that of slates, and the rock is a product of somewhat more intense or longer continued metamorphism.

Phyllites have little use. They are too soft for crushed stone, and too weak for structural uses.

*Schist.* Schists are foliated metamorphic rocks of medium to coarse texture. They are the product of the same processes of rock flow and recrystallization that produce slates and phyllites, but carried to a higher degree. In slates, the foliation is called *slaty cleavage.* The foliation of schists is called *schistosity.* Slaty cleavage and schistosity differ only in perfection and size of grain. The perfection of schistosity varies. In some schists it is excellent; in others it is relatively poor. The schists with the most perfect foliation are those with the highest proportion of the micas. The common minerals whose dimensional parallelism determines the schistosity or "splittability" are muscovite, biotite, chlorite, and hornblende. Quartz is present in most schists, but feldspar is present only in subordinate amount. The schists are frequently porphyroblastic, i.e., they frequently have metacrysts. Garnet, feldspar, tourmaline, staurolite, andalusite, and other minerals are common as metacrysts. The colors of schists vary according to the mineralogical composition, as does also the perfection of cleavage.

Schists are of little use. Because of the foliation, they are generally weak rocks. Some schists especially rich in muscovite are a source of scrap mica.

*Gneiss.* Gneisses are banded metamorphic rocks, generally of medium or coarse texture, and commonly with some degree of foliation or schistosity. Most gneisses are coarser than most schists and carry considerable feldspar.

There are many varieties of gneiss, corresponding to several modes of origin. The bands of a gneiss are generally of contrasting

mineral composition. The banding may be due to differences in the original sedimentary beds, to segregation and recrystallization of the material of igneous rocks, or to a crude foliation resulting from shearing and recrystallization. Feldspathic or granitic material introduced along bedding or foliation planes, or vein material similarly introduced or segregated, forms gneisses. In addition to the metamorphic gneisses, some igneous rocks have a primary foliation or flow structure. For these the term *flow gneiss* is sometimes used.

Many gneisses have metacrysts. Feldspar is especially common as a metacryst mineral in gneiss. Garnet, sillimanite, and other metamorphic minerals are also common, but feldspars, quartz, micas, and amphiboles are the dominant minerals of most gneisses.

The names of the individual varieties of gneiss are formed by prefixing qualifying terms. The results of *lit-par-lit* additions, for example, are frequently called injection gneiss. Similarly the term *vein gneiss* is used. If a gneiss is obviously a sheared and recrystallized granite it is a *granite gneiss*. On the other hand, if the gneissic structure is a primary or flow structure, the rock is not metamorphic and is better called a *gneissic* granite, syenite, or other igneous type.

Gneisses grade into schists. The distinction between the two is not very closely drawn. If a rock splits with a smooth surface along

TABLE 8.2. SOME COMMON METAMORPHIC TRANSFORMATIONS

| *Original* | *Sedimentary Rock* | *Metamorphic Products* |
|---|---|---|
| Clay | Shale | Slate, phyllite, schist |
| Marl | Limestone | Marble |
| Impure lime mud | Calcareous shale, or impure limestone | Lime silicate rocks |
| Sand | Sandstone | Quartzite |
| Granite | | Granite gneiss |
| Basalt | | Greenstone, chlorite schist, hornblende schist, amphibolite |

the foliation, it is a schist; if much feldspar is present it is a gneiss; if foliation is weak or absent and the rock is banded, it is a gneiss.

Some gneisses are used as building and dimension stone. If foliation is not strong, it may be used for crushed stone. Gneiss is not, however, widely used.

## Summary of Metamorphism

Metamorphic processes are gradational. A hard brittle mineral may be crushed while adjacent minerals are recrystallized. The softer argillaceous beds of a sedimentary sequence may be changed to slate or schist while comparatively little change is taking place in more resistant neighboring beds. Contact alterations are frequently accompanied by dynamic metamorphism, and vice versa. The products of metamorphism are likewise gradational. Quartzites, for example, grade into quartz-mica schists, with an increase in mica; or, if banded, they grade into quartzite gneisses. Similar gradations of carbonate rocks, from marble to schist or to lime-silicate gneiss, are common. Table 8.2 shows the common transformations of rocks.

The metamorphic processes are constructional in nature. The elements are recombined into minerals stable under high temperatures, high pressures, conditions of plastic flow, or a combination of these. In addition there may be introduction or elimination of certain elements, or both. It may be noted that the processes are a reversal of those of weathering. The end-products of extreme metamorphism may be truly igneous rocks.

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*Courtesy of Spence Air Photos*

FOLDED SEDIMENTS—THE RAPLEE ANTICLINE—PARTIALLY DISSECTED. SAN JUAN RIVER, UTAH

CHAPTER IX

# GEOLOGICAL STRUCTURES

ALL ROCK MASSES HAVE SOME FEATURES OR DESIGNS CALLED *structures*. The study of the arrangements and significance of these constitutes the field of geology termed *Structural Geology*. To the engineer, miner, and quarryman geological structures are of direct concern because the ease, method, and cost of excavation depend in part upon the structure of the material. Many surface features of the earth are related to structure, and the course and movement of underground water are, in large measure, influenced by structure.

Various types of structures can be recognized. Broadly, these are classed as primary structures and secondary structures. *Primary structures*, for example stratification of sedimentary rocks, are those structures formed at the same time as the rock mass itself or during its consolidation. Both sedimentary and igneous rocks have primary structures, and many of their metamorphic derivatives display primary structures which were not obliterated during the rock alteration. *Secondary structures* are those produced during the post-consolidation history of the rock. Secondary structures include such features as folds, warps, rock cleavage, and many types of fractures.

Although some parts of the earth's crust have been more stable than others during the long course of earth history, the internal forces of compression or uplift have affected all land areas, and probably all parts of the sea floors. Large-scale earth movements are termed ***diastrophism***. Diastrophism includes two types of movement, epeirogenic and orogenic movements. The first of these, ***epeirogenic*** movements, are dominantly vertical, up or down move-

ments, which involve considerable area but do not cause much deformation. *Orogenic* movements are those in which the horizontal component of displacement is considerable. They result in folding, mashing, and breaking of the rock masses involved. There are, of course, all degrees of deformation which range from the intense crumpling and squeezing of mountain zones to the scarcely perceptible warps of plains and plateau areas.

### PRIMARY STRUCTURES

The structures formed during deposition and consolidation of sedimentary rocks and those formed during the hardening of igneous rocks are useful indicators of the conditions under which the rock was formed and consolidated. If primary structures are present in metamorphic rocks, they aid in the discrimination of metamorphosed igneous rocks from metamorphosed sediments. Primary structures of both sedimentary and igneous rocks have been described in previous chapters, hence only brief discussion of these is added here.

***Primary Structures of Sediments.*** The most important and universally present structural feature of sedimentary rocks is layering, or stratification. The layering may be due to differences in grain size, in color, in mineralogical make-up, or some combination of these factors. Air and water carry the bulk of sediment moved from one place to another. Because these are fluid agents which differ in competency from time to time and from place to place, they sort the materials they carry according to size, weight, and grain shape—hence stratification. Some sediments, however, as those formed by direct ice deposition, are not stratified. The most widespread sediments are those deposited in shallow seas. It follows that the layers or beds were deposited in essentially horizontal position. Where deposited on sloping bottoms, the strata have an original inclination, or *initial dip*.

Sediments deposited near shore are generally coarser than those deposited offshore in deeper and quieter water. Varying strength of wave and current and irregularities of offshore slopes, however,

at many places prevent uniform seaward gradation of sediments. Storm disturbances and river floods, as well as positive and negative movements of the floors on which the sediments are deposited, also give rise to irregularities of grading. Thus it is that sedimentary strata vary not only vertically but also laterally. Terrestrial sediments, those deposited by streams, in lakes, or on land surfaces, are notably less uniformly graded than marine sediments. Many terrestrial sediments, particularly those of stream origin, are extremely variable in both plan and section.

Minor structural features of sediments, such as mud crack, ripple-mark, and cross-bedding, have already been described. Masses of unconsolidated sediments above or below water are subject to slides, slumps, and flows. These movements of unconsolidated material disturb the stratification and give rise to intricate patterns of minor crumples and faults which are commonly confined to a single bed or series of beds. When the loose material is consolidated, the evidence of soft-rock deformation is often preserved. During diagenesis (the time between deposition and consolidation), compaction, settlement, and desiccation give rise to many cracks or joints which characteristically are discontinuous and irregular in pattern.

***Primary Structures of Igneous Rocks.*** Most igneous rocks display some structures formed during the intrusion or extrusion, or consolidation period. The two principal types of these primary structures are flow structures and fracture patterns.

The primary flow structures consist of parallel arrangements of unequidimensional bodies or particles. Magmatic flow pulls these into parallel or subparallel positions. Oriented particles or bodies of plate-like or tabular shape, micas, feldspar phenocrysts, schlieren, or inclusions, give a *planar flow structure* in which the long and mean axes lie in roughly parallel planes. In many lavas, planar flow structure caused by slight differences in viscosity or composition is strongly developed. The orientation of the flow planes is determined by the direction of magmatic flow just prior to congelation and, in general, is parallel to the contacts or nearest friction exerting surface. Oriented particles of elongate, needle-like, or spindle-shape bodies

as hornblende crystals, cigar-shaped inclusions, or streaks of mica or other minerals with the long axes parallel or subparallel, give a *linear flow structure*. Both linear structure and planar flow structure may be present in the same mass, either may occur separately, or both may be megascopically absent. An igneous rock that displays streakiness or banding due to magmatic flow is often called a *flow gneiss*. Igneous rocks with primary flow structure generally split or break more readily parallel with that structure than in any other direction.

The primary fracture patterns of igneous rocks consist of joints or faults developed by the stresses associated with intrusion or consolidation either prior to or just after complete consolidation. Tension joints, normal to elongation, and hence normal to flow structure if that is present, are abundant. Minor inward or outward directed faults or breaks caused by the upward or outward thrust of the intrusive mass are found in many intrusions. Diversely oriented joints caused by contraction on cooling and solidification or by stresses associated with intrusion also are numerous. Dilatant cracking of an incompletely crystallized magma gives rise to many small pegmatite and aplite dikes, for any fluid residue adjacent to a crack is drawn into it. Many of the light-colored dikes normal to flow structure are of this origin. Numerous other joints, still later, are coated with pyrite or other minerals as a result of emanations rising along the joints from below. Dike-filled or mineral-coated fractures often aid in determining which sets of joints are primary, although, of course, not all of these are of primary type.

### Secondary Structures

Rocks yield to overpowering stresses by breaking, bending, and by solid flow. The results of the failures constitute the features of rock masses called *secondary structures*. Laboratory tests on the materials of engineering, mortar, concrete, wood, and steel illustrate the principles of rock failure. In nature, some rocks fail as plastic or ductile materials, and some fail as brittle substances. The conditions of failure, notably temperature, depth of burial or confinement,

stresses applied, and rate of stress applications, as well as the composition and crystallinity of the rock masses affected, are decisive in determining the structures which result on failure. Rocks which at the surface are brittle may, under high temperature and deep burial and when there is a slow application of stress, fail plastically.

As has been stated, rock masses subjected to overpowering stresses yield or, in the engineering sense, fail in various ways. Indeed, the manner in which rock masses accommodate themselves to overpowering stresses is not fully understood. The results of failure in terms of rock structures, however, can be reduced to rather simple terms. The rock masses either bend or break, or bend and break with or without rock flowage. If the failure is dominantly by bending, simple or complex folds result. If the failure is dominantly by fracture, there are two possibilities: the rock mass may shatter and crack without important movement or displacement along the breaks—a failure analogous to the cracking of shatterproof glass; or the rock mass on one side of a fracture may be displaced in the plane of the fracture relative to the mass on the other side. The first type of fracturing is called *jointing;* the second type is called *faulting.* The principal secondary structures of rocks therefore are folds, joints, and faults.

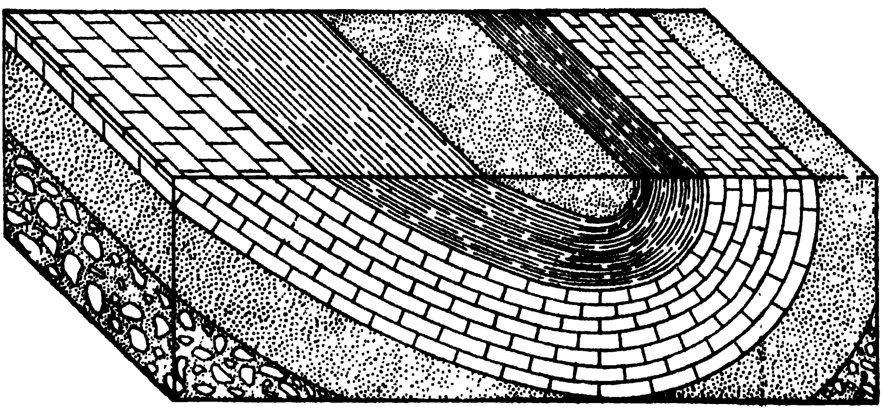
***Folds.*** Folds vary from slight flexures of simple outline to intricate folds made up of many minor folds. Scale, likewise, varies from minute crenulations a small fraction of an inch in length to grand features miles in length and several miles across. The primary types of folds are upfolds, or *anticlines;* downfolds, or *synclines;* and abrupt flexures or changes of inclination of horizontal or uniformly inclined beds known as *monoclines.* Anticlines and synclines are commonly complementary. If, as has happened at many places, folds are eroded, older beds appear in the central parts of eroded anticlines than at the outsides; in eroded synclines, the younger beds appear in the central part of the structure. The relations are shown in Fig. 9-1.

***Principal Parts of Folds.*** In the study of folds it is convenient

to recognize a number of fold elements or principal parts. These are the limbs, axial plane, and axis.

The flanks or sides of folds are called the *limbs*. The structural attitude of the limbs (or of any inclined, near-plane surface, as a dike, sill, fault, or other plane feature) is expressed by strike and

9-1A



9-1B

FIG. 9-1. Eroded syncline. Note cleavage intersecting the bedding and subparallel to axial plane of fold. (Photo by E. H. Perkins)

dip. The *strike* is the *direction* of the line of intersection between a horizontal plane and the considered plane (bedding surface or bedding plane); stated otherwise, it is the direction of a level line on the inclined surface. The *dip* is the maximum angle of inclination of the considered surface (bedding plane) measured from the horizontal. The direction of dip is always at right angles to the strike. Dip and strike of inclined beds are illustrated in Fig. 9-2. In the field study of structures, the mapping of dips and strikes is the usual approach to structural analysis. However, if the beds are intricately folded, several hundred dip and strike determinations may not suffice to outline the folds in an area of even a few hundred square feet; hence other more constant elements of folds are important.

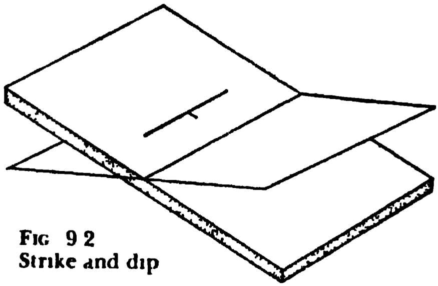


FIG 9 2
Strike and dip

The *axial surface*, commonly called the *axial plane*, is the surface which most nearly divides the fold symmetrically lengthwise. It may be a plane or warped surface, and it may be vertical, or it may be inclined. If the axial plane is vertical, the fold is upright or symmetrical; if the axial plane is inclined, the fold is overturned and asymmetrical. The intersection of the axial plane with the crest or trough of a fold is called the *axis*. The axis may be horizontal, or it may be inclined. The angle of inclination of a fold axis, measured from the horizontal, is called the *plunge* of the fold. The plunge is therefore a special case of dip measured on the crest or trough of a fold. The limbs, axial plane, and axis of a fold are shown in Fig. 9-3. The structural attitude of the axial plane is defined by its dip and strike, the structural attitude of the axis by the direction of the axis, projected to a horizontal plane, called the trend or strike of the axis, and by the direction and amount of plunge. From the relations of Fig. 9-3 it will be seen that unless the axis of a fold is horizontal, the trend of the axis and the strike of the limbs are not parallel. Further consideration will show that where folds die out or

disappear, they have a plunge; at the ends of every fold the axes are inclined unless the fold is cut off by a fault or intrusion

The dips and strikes of folded beds may vary rapidly from place to place, even within short distances The attitudes of the axial planes and the trend and pitch of fold axes, however, commonly remain parallel or subparallel over considerable areas. And it may be further noted that the axial planes and axes of the little folds

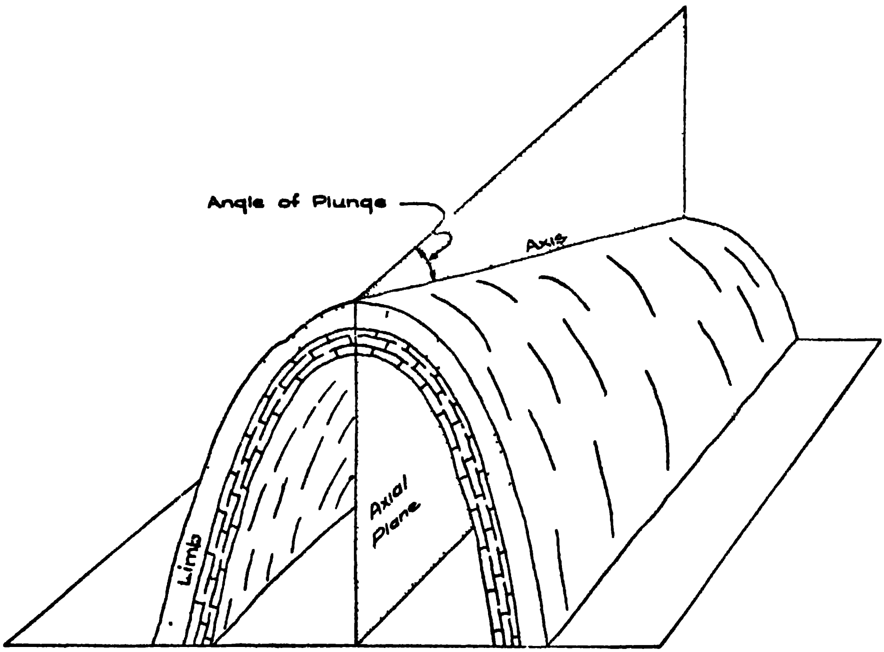



FIG. 93. Anatomy of a fold

that can be seen and measured in the single outcrop, even of the minute folds, give measurements applicable to the larger folds of the region which are inferred and demonstrable but never seen in their entirety. The little structures reflect the big ones.

*Mechanics of Folding.* Folding of sediments takes place by several different means of accommodation to stress. In many folds, there has been a slip or shear between the layers. This is illustrated by the slipping of cards over each other as a deck is folded If the

cards are not permitted to shear over one another it is impossible to fold the pack Other folds are accompanied by a thinning of the flanks and thickening at the crest, rock flowage, or plastic deformation, is indicated In general, slips between the beds accompany the folding of strong, competent rocks (as quartzite) thickening and thinning of beds, rock flow, accompany the folding of weak incompetent rocks (as shale) The folds of strong competent types of rock tend to be broader and simpler in outline than those of weak incom

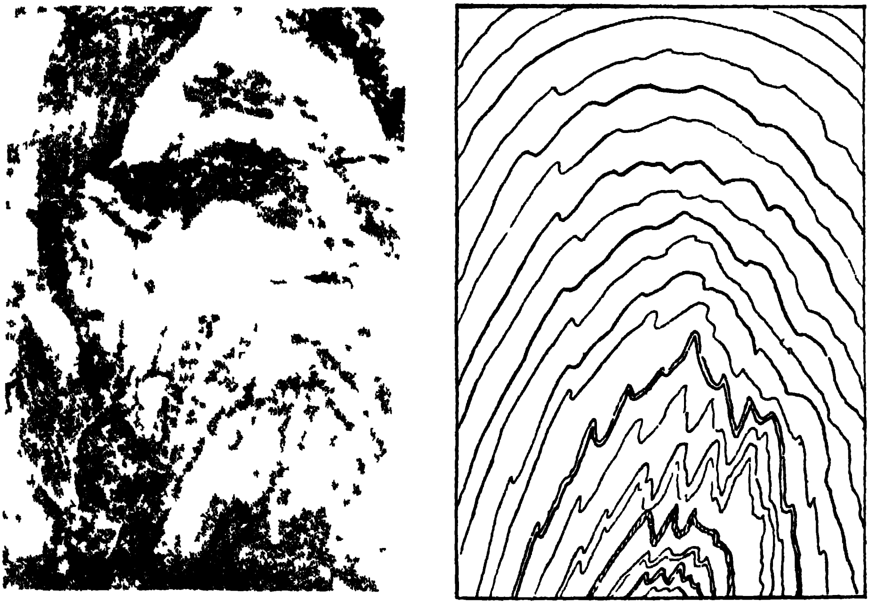


FIG 9 4 Competent and incompetent beds in fold

petent types It frequently happens that strong and weak layers, for example quartzites and shaly beds, alternate in a sedimentary series. Generally the more massive, competent members make folds with relatively simple outlines, whereas the intercalated weaker members make folds of much more intricate pattern A small scale example of this is illustrated by Fig 9 4

Beds may be displaced along closely spaced shearing fractures in such a way as to produce apparent folding This may be illustrated by ruling a line across the side edge of a deck of cards and

pushing up the middle cards from the end of the pack. The ruled line takes the form of an anticline. This type of structure, called a *shear fold* (Fig. 9-5), does not, however, imply folding in the ordinary sense of the word. Many folds in metamorphic rocks probably have a minor component of shear folding due to displacements along cleavages parallel to the axial planes of true folds.

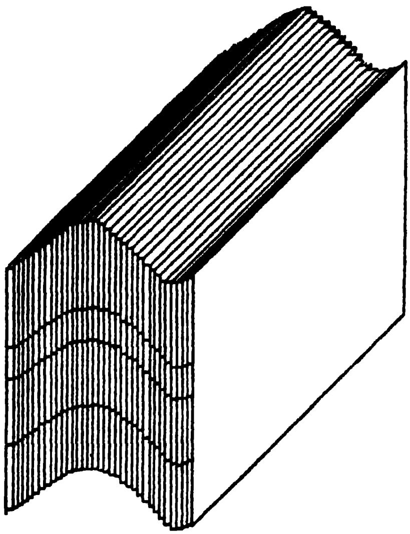
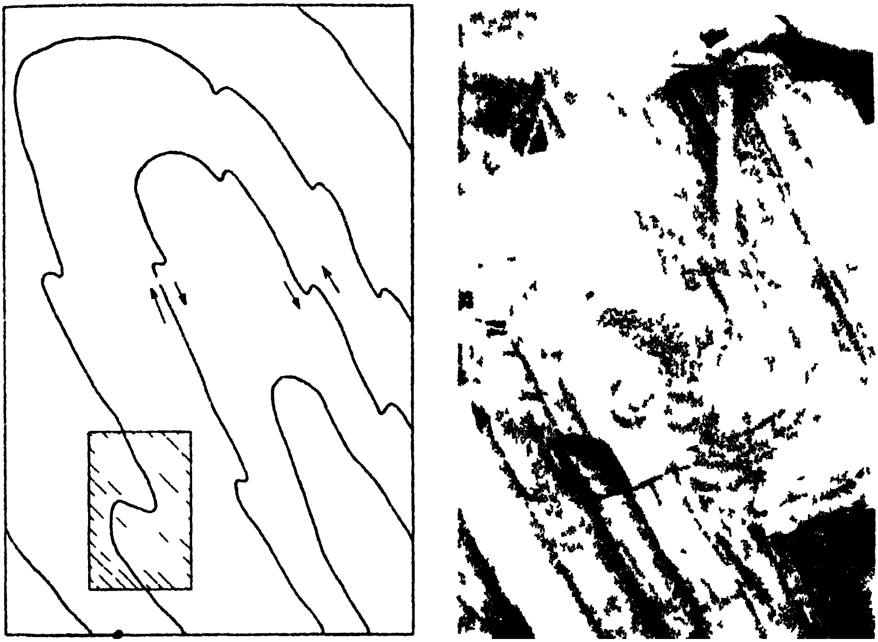


FIG. 9 5 Shear fold

*Identification of Folds.* At many places where rocks have been folded, erosion has truncated the structures and the synclinal or anticlinal nature of a fold must be inferred If the folding is open, the reversal of dips often suffices to identify the fold If the folding is close, i.e., the limbs are so tightly appressed as to bring opposing limbs in contact, detailed observations are necessary to determine synclines and anticlines. Structures which aid in making the inference are drag folds, rock cleavage, and sedimentary details which tell which side of a bed was originally the top and which was originally the bottom.

*Drag Folds.* In many folds, weak layers are thrown into minor undulations, called *drag folds,* illustrated in Fig. 9-6. It is note-

worthy that drag folds are asymmetric, and by their asymmetry indicate the relative displacement of adjacent layers. In the folding of a pack of cards it will be noted that each card moves up towards the crest of an anticlinal fold relative to the card just beneath it. In a synclinal bend of the cards, each card moves towards the trough relative to the card just above it. Because the same type of relative



A B

Fig. 9.6. Drag fold. The cross-hatched area at the left is shown in detail at the right.

movement or shear takes place between beds in the folding of sediments, it is frequently possible to use drag folds to determine on which limb of a syncline or anticline a considered exposure lies, as was shown in Fig. 9.6. A great many field observations have shown that the axial planes of drag folds tend to parallel the axial planes of the larger folds to which they are related. It has been further shown that the axes of drag folds tend to be relatively uniform in direction and plunge throughout large areas and are, for the most part, subparallel to the axes of the major folds. There are all scales

of drag folds. Many drag folds are related to larger folds which are themselves drags related to yet larger structures. One of the cardinal principles of structural geology is that the smaller elements commonly simulate the larger ones.

*Rock Cleavage.* When shear between beds occurs, whether related to folding or faulting, a complementary system of fractures often develops. In the weak beds, these fractures are often closely spaced. These closely spaced joints give the rock a capacity to split in thin sheets, i.e., they impart a *fracture cleavage.* Fracture cleavage, when developed in the course of folding, indicates the relative displacements or shear between beds in much the same way as do drag folds and is therefore a useful clue in the determination of folds. The plane of fracture cleavage gives a rough approximation of the axial plane of the fold, and hence its intersection with a bedding plane gives an approximation of the plunge of the fold. The formation of schistosity or flow cleavage has been discussed in the chapter on metamorphic rocks. Flow cleavage parallels more perfectly the axial planes of folds to which it is related than does fracture cleavage. The relation of cleavage to folds is shown diagrammatically in Fig. 9-7. In folds that have been so tightly compressed that the beds of

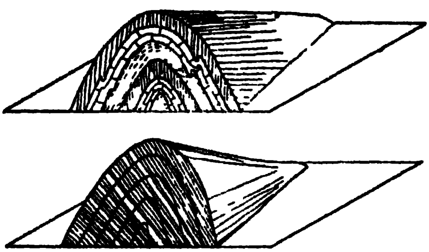


FIG. 9-7. *Above:* Cleavage related to folding. *Below:* Cleavage not related to folding

the opposite flanks are parallel, cleavage on the flanks is parallel or so nearly parallel to the bedding as to be of little use. At the nose of the fold, however, i.e., where the fold closes with convergence or divergence of the beds in plan, cleavage and bedding are at an angle to each other, and the relations are useful. It should be remembered that fracture and flow cleavage can be superimposed on a region after the folding has been accomplished and, consequently, are not

necessarily related to the folds. If, for example, as shown in Fig. 9-7, the cleavage cuts across a structure, it may be assumed that folding and cleavage are unrelated.

FIG 9 8. Fracture cleavage intersecting bedding.

*Sedimentary Details.* The tops of the beds face outwards from the axial plane of an anticline, and inwards towards the axial plane of a syncline. In a sequence of sediments, therefore, minor structures that tell which side is the top of the bed distinguish on which side of a fold the exposure lies. Cross-bedding, oscillatory ripple mark, and grain-sized gradations are often found and are commonly diagnostic. The determination of tops by cross-bedding and oscillatory ripple mark is indicated by Fig. 9-9. The laminae of cross-bedding are truncated on the top side and turn tangential to the true bedding on the bottom side. The crests of oscillatory ripple mark, tops, are sharper than the troughs. Many sedimentary layers are coarser-grained at the bottom than at the top. And although this criterion is less reliable than cross-bedding or oscillatory ripple mark, it is often useful.

***Rock Fractures.*** Rocks often rupture under stress, failing in tension or shear or both. If there is no significant movement parallel to the rupture surfaces, the break is called a *joint*. If the rock masses on opposite sides of the rupture are relatively displaced, the break is called a *fault*. Both joints and faults are structures of practical interest, for in addition to determining the ease and costs of excavation, groundwater moves along them, and along them alteration proceeds.

*Joints.* Attention has been called to the joints of both igneous and sedimentary rocks formed in the early stages of the rock history. The primary joints of sediments, formed during consolidation, compaction, and desiccation, were characterized as being typically short, discontinuous, and irregular in pattern. Weathering of consolidated rocks produces joints that are likewise short, discontinuous, and irregular. In contrast, joints that are developed as a response to overpowering stress are frequently quite regular in pattern, often long, and at many places strikingly geometric in plan. Regular joint patterns are found, however, in many essentially horizontal sedimentary rocks. Joints are also very common parallel to the bedding planes of sediments. In shales, bedding plane joints are so closely spaced that shales are said to have *fissility*. Ready planes of parting parallel to the bedding are usually present between rock layers of different types, for example between muddy and sandy layers or between muddy and limy layers.

Almost all folding is accompanied by some fracturing. The shear between beds has been noted in the discussion of folds; and the development of fracture cleavage, really a form of close jointing, has also been mentioned. During folding, the more massive, or more competent, beds are often fractured while the weaker less competent members fail plastically. Along the crests of anticlines longitudinal tension cracks, parallel to the axis of the fold can often be noted. Underneath the crest, i.e., below the neutral plane, compression joints form which are tighter and less conspicuous. On the limbs of folds, the brittle members often display both tension and shear joints; often an analysis of the joint patterns enables the structural

geologist to infer the associated structure which may be concealed by overburden. A regular pattern developed in course of folding is shown in Fig. 9-10.

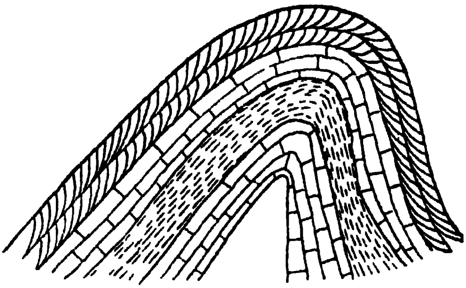


FIG. 9-9 Relation of cross bedding to fold

FIG. 9-10 Joints related to folding.

Joints of all types serve as avenues of percolation for ground water. Many veins are found where ground water has filled joints with mineral matter. Calcite and quartz veins are common types of joint fillings. In soluble rock, joints are enlarged by solution. It is probable that most caves and sink holes in limestone are results of solution which started along joints.

Because of the complexity of joint systems in many areas, the use of joints in inferring the larger structures and the deformational history of the rocks is difficult. Careful measurements of many joints, however, may reveal a pattern made up of two, three, or more sets of parallel joints. At many places, joint systems can be related to one another according to common experience in testing engineering materials. Thus two sets of vertical joints are found; one set strikes N 50° W, the other strikes N 50° E. A third set of joints, also vertical, strikes east. The northeast and northwest sets approximate

the planes of maximum shear, and the east striking set corresponds to the tension plane of the strain ellipsoid. The mean axis is therefore vertical; the maximum elongation in the north-south direction, and greatest shortening is east-west. If the maximum elongation (direction of easiest relief) is horizontal, deformation at considerable depth is a fair inference. Note that no inference is drawn as to the direction of applied stresses responsible for the deformation.

*Faults.* Fracture surfaces along which movement has occurred are termed *faults.* Some are clean sharp breaks. Many, however, are composed of subparallel faults among which the total displacements have been distributed. The terms *shear zone* or *fault zone* are often applied to closely spaced subparallel structures along which there has been distributive movement. Some faults, even large ones, are knife-like breaks. Other faults, because of the frictional effects of rock masses sliding over one another, break or crack (brecciate) the rock on either side of the rupture. Still other faults pulverize the rock in the fault zone to clay-like powder called *gouge.* Conventionally, the surface of rupture along which relative movements have taken place are termed *fault planes.* Most fault surfaces, however, are warped or curved and irregular in detail; the term *fault surface* is preferable to *fault plane.* The movement along or on the fault surface may be in any direction, and the total displacement on many faults is a cumulative result of intermittent dislocations. Indeed, spasmodic movements along many faults are continuing to the present, as witness the displacements along the San Andreas Rift within the present century.

Locally, water mains, bridges, dams, and other structures have been built across faults on which renewed movements have caused damage or destruction. A fault is considered *live* if displacements have occurred along it within historic time, whereas a fault on which no recent slipping has taken place is considered *dead.* The probability of recurrent movements on faults encountered in engineering practice is of special concern to the engineer. The construction of tunnels through fault zones or of dams on faulted foundations has often been difficult and expensive. Much of the "bad ground" in

tunnels and much excessive leakage into them are along faults. Faults have increased the necessary preparation of dam foundations, both by grouting and excavation. They have retarded construction, increased the difficulties of carrying it out, and have added to construction costs both directly and indirectly.

*Fault Types.* Faults are classified in a number of different ways, and no classification is entirely satisfactory. One of the simplest ways of classifying faults is by reference to the relative movements of either side of the fault surface, which is either vertical or inclined at some angle. If a fault surface is inclined, the upper side is called the *hanging wall* and the lower side is called the *foot wall.* The terms come from old mining usage. Many faults have been mineralized by waters which circulate along them, and many mining operations therefore have followed faults. In such a mine the upper side of the fault was hanging overhead, hence hanging wall; the lower side was under foot, hence foot wall. Vertical faults have neither hanging nor foot wall. If the hanging wall has moved down relative to the foot wall, the fault is called a *normal fault.* If, on the other

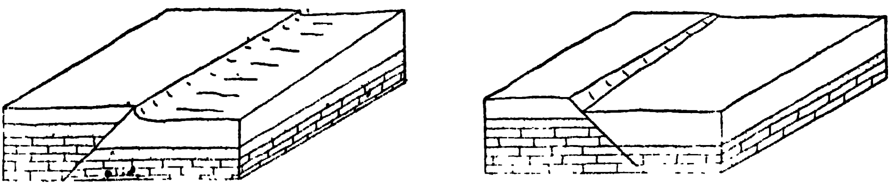
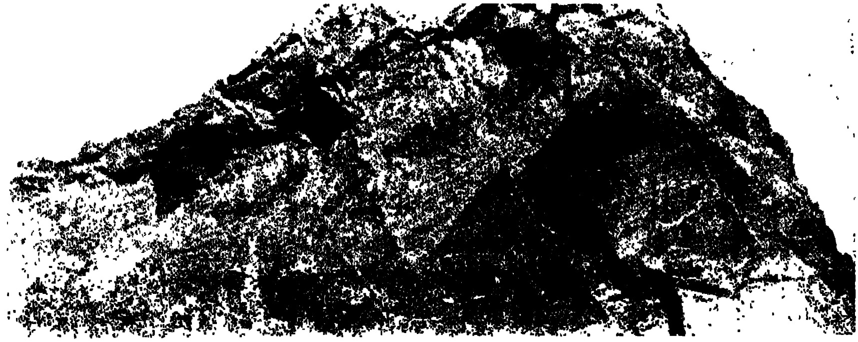


FIG. 9-11. *Left:* Cross section of reverse fault. *Right:* Cross section of normal fault. *Below:* Normal faults in unconsolidated sediments.



hand, the hanging wall has gone up relative to the foot wall the fault is called a *reverse fault*. The relations are shown in cross section in Fig. 9-11. It will be noted that the term *relative movement* has been used. In few faults is it possible to tell which wall has actually moved. Faults with vertical fault surfaces are called *vertical faults*. Where an elongate block is dropped down between two normal faults of subparallel strike, the structure is called a *graben*. Where a central block is upthrust between two normal faults, the structure is a *horst*. Horst and graben structures are illustrated in Fig. 9-12.

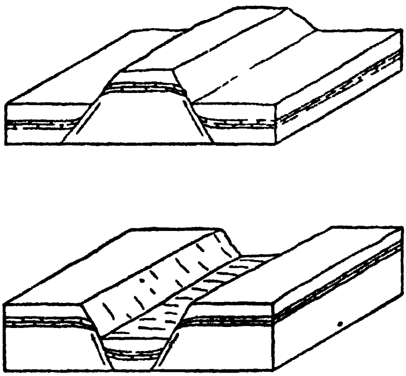


FIG. 9-12 *Above* Horst *Below* Graben

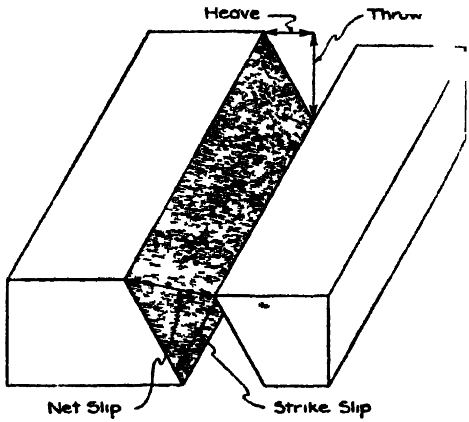



FIG 9-13 Components of fault displacement

*Description of Fault Movements.* For convenience in describing the actual displacements or recording measurements, fault displacements are referred to three mutually perpendicular axes, two horizontal and one vertical. One horizontal axis lies parallel to the strike of the fault; the other consequently is normal to the fault strike. The horizontal displacement, measured along the strike of the fault is called the *strike slip;* the horizontal displacement measured normal to the strike of the fault is called the *heave*. The vertical component of the net slip is called the *throw*. The true displacement, measured along the fault surface between two points contiguous before faulting, is called *net slip*. Although the net slip of many

faults is directly down the dip of the fault and of others is parallel to the strike of the fault, the net slip may be at some angle between the directions—a diagonal slip as shown in Fig. 9-13 which illustrates the naming of the components of fault displacements.

*Mechanics of Faults.* Faults are shear failures which result from tensional, compressional, or rotational stresses acting on a rock mass. Although normal faults are sometimes referred to as *gravity* faults, the only examples where the term is strictly applicable are landslides and collapse structures both of which are types of normal fault. Normal faults are sometimes called *tension faults,* and reverse faults called *compressional faults.* It is well known, however, that tension failures may result from compressive stresses; terms implying tension or compression as causes must be justified by field evidence before they are applied

Reverse faults commonly dip less than 45°, whereas normal faults commonly dip at angles steeper than 45°. The explanation for this is shown in Fig. 9-14. For the reverse fault, the causal force

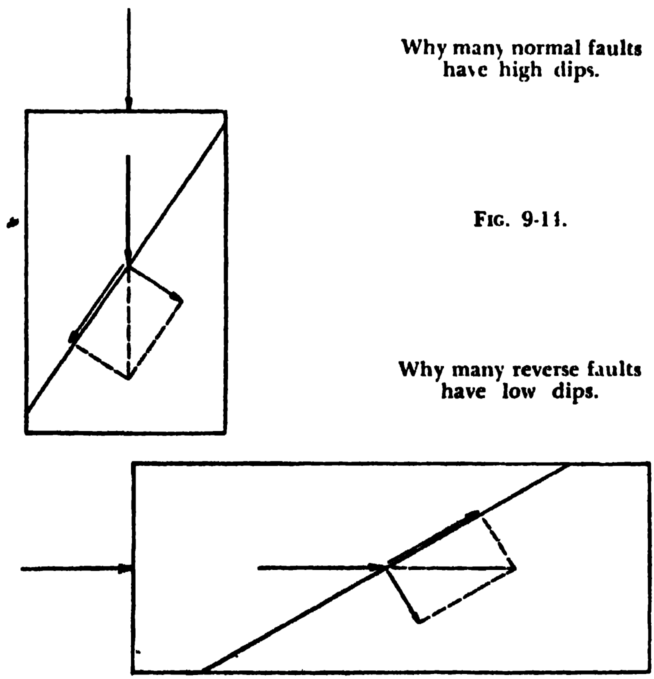



FIG. 9-14.

is shown as horizontally directed. The sliding component is greater, and the normal component which tends to hold the blocks together and inhibits movement is less if the fault dips at an angle less than 45°. For the normal fault, the causal force is shown as vertically directed, hence the angle of dip greater than 45°. Although the direction assumed for the causal stresses in these illustrations may be correct for many faults, it should be remembered that there are other possibilities, and steep angle reverse faults are not uncommon.

The underlying causes of earth stresses of great magnitude are not yet well understood. It is a matter of common observation that faults are abundant in volcanic areas and mountain zones. Faults are not limited to these two types of region however, they are found also in plains and plateau areas.

***Evidence of Faulting.*** Many faults are difficult to detect in the field. Many and perhaps most faults delineated on maps are the result of inference rather than direct observation. Roughly these observations can be divided into two groups: lithologic, which suggest or establish faults, and physiographic evidences.

*Lithologic Evidence.* A variety of lithologic features are associated with faulting. Among the most significant are slickensides, brecciation and gouge, shear zones, displacements, and drag.

*Slickensides.* A fracture surface on which movements have taken place may locally display parallel striations or grooves called *slickensides*. A slickensided surface is generally well polished by the frictional rubbing of one block by the other. The direction of movement is indicated by the trend of the striae, and the direction of relative displacements can be determined from many slickensided and polished fault surfaces by passing the hand over the surface to find the rough and smooth directions. A slickensided surface from which a determination of the direction of relative displacements can be made by this method is shown in Fig. 9-15. Fault striae resemble glacial striae (Fig. 9-16), but are found in situations where glaciers could not have scoured the rock. Inasmuch as the advance of glacial ice is a form of low-angle faulting, glacial striae are a type of slickensiding. Slickensides may be made by relatively slight dis-

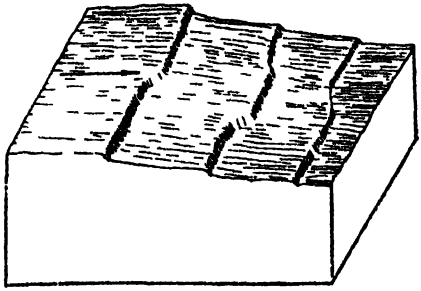


Fig. 9.15 Slickensided surface showing relative movement. Note step-like surface, exaggerated in diagram.

Fig. 9.16 Slickensided surface.

placements they do not necessarily indicate dislocations of great magnitude. And because they record the direction of the latest relative movements on the fault, they may or may not coincide with the direction of *maximum* displacement. In general, however, slickensides are good evidence of the direction of fault movements.

*Brecciation.* Along some faults the rocks are highly fractured or even crushed to angular fragments called *breccias*. An elongated zone of brecciation which transects bedding suggests faulting. The dimensions of fragments which constitute a fault breccia are extremely variable. The individual blocks of some fault breccias are measured in tens of feet; at the other extreme, perhaps originating at greater depth, are fragments of minute size. A very fine, claylike product of fault crushing is called *gouge*. Neither fault breccia nor gouge is present along all faults. Indeed, numerous major faults have been investigated that show little or no associated brecciation or gouge.

*Shear zones.* Many faults are characterized by closely spaced fractures among which movements have been distributed. Fracture or shear zones are suggestive evidence of faults. At many places,

weathering along the fracture zone is more advanced than in the adjacent rock. Much of the difficulty in engineering construction in fault areas stems from the altered or rotten rock encountered.

Because fractures offer avenues of ready percolation for circulating waters, many mineral deposits have been localized along faults. The shear zones of some faults are silicified by more or less complete replacement along the zone, or by a network of quartz veins which fill the fractures. Many ancient faults have been completely sealed and healed by mineral fillings and replacements.

*Drag.* Minor folding of strata along the walls of a fault, caused by the fault displacement, is called *drag.* Thus, in an area of regular structural attitude, one of horizontal beds, for example, abrupt changes of attitude suggest drag associated with faulting. In areas of complexly folded rock, the evidence of drags loses weight.

*Dislocations.* It is possible to observe actual dislocation of strata, veins, or dikes and to match the ends of dislocated parts along some faults of small displacements. Stratigraphic anomalies of larger scale may be brought out in the course of field mapping. The repetition or elimination of recognizable beds often establishes the break, as shown by Fig. 9-17. An abrupt termination of structures, as folds, beds, or dikes along a common line or zone, suggests faults, as does the juxtaposition of rock types in anomalous relations, as for example metamorphic rocks and sedimentary rocks without transition types. Other possibilities and alternative explanations, however, should not be overlooked. Any structural tangle in mapping can be resolved by drawing faults on the map. Good practice, however, is to assume a concealed fault only after all other possibilities have been explored and tested.

*Physiographic Evidences.* Landscape forms, or physiographic features, although seldom conclusive, may be suggestive of faulting and therefore helpful either when seen in the field or recognized on maps or aerial photographs. Escarpments and other suggestive topographic features, therefore, are of interest in a consideration of faulting.

*Escarpments* are linear forms of abrupt increase of slope. Escarp-

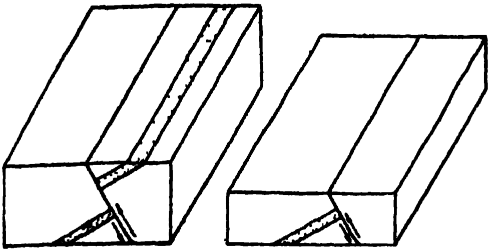


Fig. 9-17A. Elimination of beds by faulting and erosion.

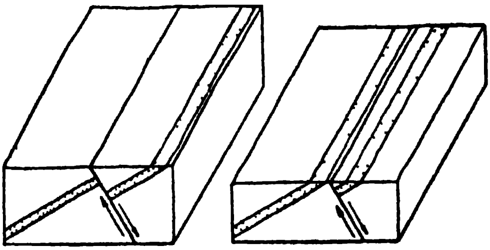


Fig. 9-17B. Repetition of beds by faulting and erosion.

ments that result from faulting are of two general types, fault scarps and fault-line scarps. An actual surface of displacement may stand up as an escarpment essentially unmodified by erosion. This constitutes a *fault scarp*. The inclination of the slope varies more than the dip of the fault itself because erosion softens, or flattens, the slope. Beginning students are often inclined to interpret any cliff as a fault scarp. It should be borne in mind that cliffs are formed in many ways entirely unrelated to faulting, for example by marine erosion, by glacial action, or by stream cutting. Associated features of faulting—dislocated beds, shear zones, slickensiding, and others—establish the origin of the scarp. Triangular facets, as illustrated by Fig. 9-18, are locally found as a result of dissection of fault scarps. Fault scarps are found only where faulting has been geologically very recent. Earthquake centers coincident with escarpments are suggestive evidence of fault origin. Escarpments in unconsolidated deposits, e.g., alluvial fans or lake fills, are also suggestive of recent faults.

*Fault-line scarps* are those etched out along the break by subsequent erosion. Faults frequently bring together resistant and nonresistant rocks. Long-continued erosion leaves the harder or more

U. S. Geol. Survey

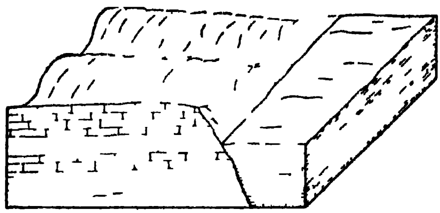


Fig. 9.18 Triangular facets caused by erosion of fault scarp

resistant beds in relief thus forming a linear scarp along a fault zone If it can be determined that the scarp faces the upthrown side of the fault, it certainly is a fault line scarp and not a fault scarp If the correlation between topography and rock resistance is well defined, the escarpment is probably a fault line scarp

Particular care should be taken in the discrimination of fault scarps from fault-line scarps by engineers concerned with structures subject to earthquake damage, or structures which cross the fault. This is because faulting recent enough to leave fault scarps may be expected to recur Renewed movements may take place on faults marked by fault line scarps, but the danger is less than on more recent faults The hazard of renewed movement must be especially considered for such structures as oil lines, tunnels, or aqueducts

which cross faults. For ease of repair in event of damage, the aqueducts which divert Colorado River water to supply the city of Los Angeles have been brought to the surface at a number of places where they cross faults that are considered possible loci of renewed movement.

*Other Topographic Evidence.* Offsets of ridges, parallel deflections of valleys, reversals of drainage, and linear depressions may suggest the presence and approximate location of a fault. Along many recent faults, linear depressions or shallow troughs, bounded by fault scarps are found; and along some recent faults springs are linearly distributed.

It should be re-emphasized that physiographic evidences of faulting are seldom conclusive. The more recent the faulting, the better the physiographic evidence. Taken in conjunction with other evidence, physiographic criteria of faulting are helpful and significant.

***Unconformity.*** Another type of structure, also due to diastrophism, merits brief description. Sedimentation is an interrupted process; nowhere on earth has there been discovered an uninterrupted sequence of sediments which marks continuous deposition. Major breaks in sedimentation are called *unconformities* Two types

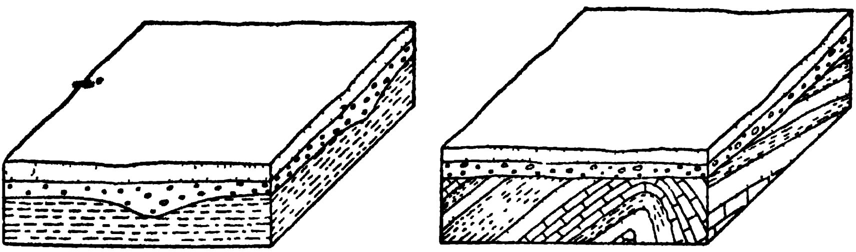


FIG. 9-19. *Left:* Disconformity. *Right·* Angular unconformity.

of unconformity are recognized, the disconformity and the angular unconformity.

A *disconformity* is a time. break in a sequence of beds; beds which should be present representing the time interval of their deposition are lacking either because of nondeposition or because

*they were eroded before succeeding beds were deposited (Fig. 9-19A).* For example, a normal sequence of beds worked out for an area consists of beds *A, B, C, D,* and *E,* each of which represents a considerable time of accumulation. The record of deposition is continuous from the bottom of *A* to the top of *E.* Subsequent field work shows that in an adjacent area beds *A, B, D,* and *E* are present, but *C* is missing. Either it was not deposited or was deposited and eroded before *D* was deposited. In either event, the time record as shown by the strata is not complete. A common cause of disconformity is uplift which raised the area above water. To distinguish disconformity careful stratigraphic studies are necessary.

*Angular unconformity* is essentially similar to disconformity but easier to recognize. In angular unconformity, as shown by Fig. 9-19B, the sequence of beds is also interrupted. During the time interval represented by the unconformity, however, not only were certain beds not deposited or deposited and eroded, but deformation and erosion also took place in the time between the deposition of the youngest of the lower series and the oldest of the upper series.

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# CHAPTER X

# EARTHQUAKES

A TYPE OF EARTH MOVEMENT THAT LOCALLY GIVES RISE TO engineering problems is the earthquake. Earthquakes are vibrations or tremors of the earth. A great many small quakes are vibrations artificially induced by heavy street traffic, by railway trains, or by similar disturbances. Explosions also cause artificial earthquakes. The use of vibrations generated by explosives in subsurface exploration for favorable oil structures, for depth to bedrock, and for various other purposes is described in Chapter XII. In general, man-made earthquakes are felt over very limited areas. In contrast, natural earthquakes which result from a sudden release of energy within the earth may be felt over wide areas. Some of the greater shocks have been perceptible over areas of more than a million and a half square miles. Other natural quakes, to be sure, have been localized within areas of a few square miles. The toll of life and property taken by earthquakes within historic times is enormous. A single Japanese quake, in 1923, caused a loss of life placed at 140,000 and a property damage estimated at three billion dollars.

## CLASSIFICATION

Although natural quakes have a variety of minor causes, two principal genetic classes are recognized: volcanic earthquakes and tectonic earthquakes.

***Volcanic Earthquakes.*** Shocks which result from explosions incident to the eruption of a volcano or from violent subterranean movements of lava are termed *volcanic earthquakes*. These may be

violent and locally destructive but are commonly felt over very limited areas. An example of this type of quake is the Fondo Machia (Sicily) quake of 1911 which destroyed the buildings within an area three miles long and a quarter mile wide, but was not felt six miles away.

***Tectonic Earthquakes.*** *Tectonic earthquakes* are those due to sudden dislocations of large blocks of rock. When rocks are stressed

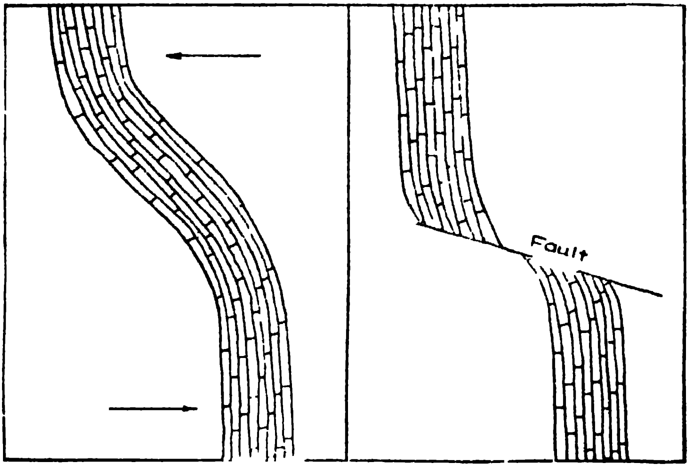


FIG. 10-1. Elastic rebound origin of earthquakes.

beyond their elastic limit sudden relief by breaking, or faulting, allows the rock masses on either side of the break to rebound elastically to positions wholly or partially relieving the strain; Fig. 10-1 illustrates this origin of earthquakes. Tectonic quakes constitute most of those felt over great areas. The San Francisco quake of 1906, the Charleston, South Carolina, quake of 1886, and the New Madrid earthquake of southeastern Missouri in 1811, are famous American examples of tectonic earthquakes which were felt over thousands of square miles.

## Geographical Occurrence and Frequency of Earthquakes

Since the beginning of the twentieth century, seismologic data have been rapidly accumulating and have been brought together

into accessible form through the co-operative efforts of seismologists. Maps showing the locations of the earthquake epicenters bring out strikingly two major belts in which the majority of recent earthquakes have originated. The first of these major earthquake belts encircles the Pacific basin and coincides approximately with the distribution of active and recently active volcanoes and with the belt of young and growing mountains. The second major belt of earthquake occurrence extends from southern Spain through the Mediterranean area, and continues eastward along the Himalaya Mountains into eastern Asia, where it branches; the principal branch passes southward through the Malay region to the Dutch East Indies, merging with the circum-Pacific belt. The frequency of earthquakes varies from year to year. On the average, a major earthquake happens somewhere every six or seven days. Minor quakes are exceedingly numerous. Japan has experienced as many as 12,000 in a single year—most, of course, very mild. California experiences many shocks of varying intensity each year, although few Californians have mentioned the fact.

Earthquake distributions in the geologic past have been quite different from the present distributions just outlined. That this is so is shown by the distribution of faults and volcanic rocks in zones now comparatively free from seismic disturbance and completely inactive volcanically. There is no place on earth, however, entirely free from seismic disturbance to-day.

### Associated Phenomena

It has frequently been noted that in alluvial areas temporary springs and sand boils occur in association with earthquakes. It has already been pointed out that vibration is the most effective way of increasing the density of granular aggregates. The natural vibrations induced by the passage of earthquake waves cause open-packed granular material to compact, and, hence, water may be expelled and subsidence of the surface may be perceptible.

Landslides have been started by earthquakes at many places. One of the most disastrous series of landslides in history took place in Kansu Province, North China, as a result of the 1920 earthquake

there which was strong enough to be felt over 1,500,000 square miles and was of destructive intensity over an area of 15,000 square miles. Thousands of people who were living in caves dug in silt were buried alive.[1]

Many waves which have done great damage along some coastlines are generated by submarine earthquakes. These destructive sea waves, called *tsunamis,* have been particularly damaging on the coasts of Japan, Chile, and the Hawaiian Islands. Tsunamis in the Pacific have been estimated to travel about 450 miles per hour. Their effects on man-built structures are so well known as to need no particular comment. Not all "tidal waves," however, are the result of earthquakes. Some are generated by volcanic explosions, and some are wind waves of unusual size.

## Earthquake Waves

Earthquake vibrations are set up or start from a limited area and are propagated outward in all directions. This central area of initiation beneath the earth's surface is called the *focus* or *focal area.* The ground surface directly above it, where shaking is most intense, is called the *epicenter* or *epicentral area.* The foci of the majority of earthquakes are at depths of less than 10 miles Many quakes originate at depths between 10 and 30 miles, however, and recent work has shown that some quakes originate at greater depths; the centers of a few have been estimated at more than 400 miles below the surface.

The vibrations travel through rock as elastic waves of a variety of types. The fastest wave, which travels with about the same speed as sound would through the same rock, is a longitudinal or compressional wave; the rock particles vibrate back and forth in the direction of wave propagation. This is called the *P, primus,* or *preliminary* wave. A second type of wave, which travels at a slower rate, is a transverse wave; the rock particles vibrate at right angles to the direction of propagation. This is called the *S, secondary,* or

[1] For a graphic account of this diaster, see Close, Upton, and McCormick, Elsie, "Where the Mountains Walked," *National Geographic,* Vol. 41, 1922, pp. 445-464.

*shear* wave. Daly[2] has graphically likened this wave to the shaking of a carpet in which the movement of a particle in the carpet is up and down, at right angles to the direction of wave propagation. A third type of wave, an induced wave, travels along the upper surface of the disturbed rock; this wave is slower and longer than either the *P* or *S* waves and of greater amplitude. It is called the *L*, *surface*, or *long* wave. The preliminary and secondary waves, longitudinal and transverse, travel through the earth by the same paths and with constant speed ratios. Thus, given the difference in time of arrival of the *P* and *S* waves at a given station, it is possible to calculate the distance from that station to the earthquake center. Practically, this distance is read from empirical time-travel curves. If the distances are established from three observation stations, the center of disturbance can be closely fixed.

In the transmission of earthquake waves, the orbits described by individual rock particles are of small magnitude, generally less than an inch. It is well known that more damaging effects are manifested on filled ground, such as alluvial deposits or artificial fills. This magnification of effect has frequently been likened to the quaking in a bowl of jelly that can be induced by vibrations of small amplitude. Eyewitness accounts of some quakes have stated that actual earth waves, comparable to sea waves, have been seen and felt moving along the earth's surface.

Earthquake vibrations are recorded by instruments called *seismometers,* of which numerous models are in current use. Most of the modern instruments have a high degree of precision and great sensitivity. The principle involved in recording earthquake vibrations is shown schematically in Fig. 10-2. Precise timing is possible, and synchronization of times at different receiving stations has given valuable aid to earthquake studies. The vibrations detected by seismometers are commonly recorded on photographic paper as a series of zig-zag lines. These records, called *seismograms,* show the vibratory impulses and the time of initiation and duration; they also depict the arrival of the different wave types. Earth shocks are

[2] Daly, R. A., *Architecture of the Earth*, 1938, p. 43.

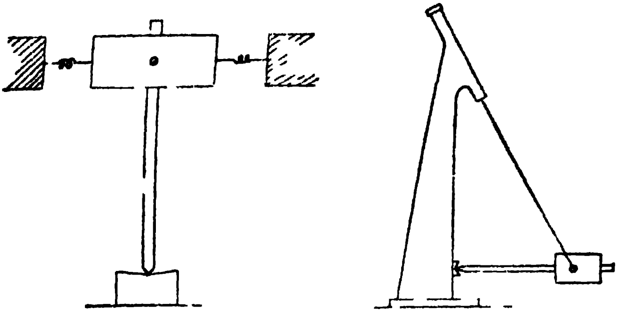

FIG. 10.2 Horizontal and vertical seismometers (Reproduced by permission from N. H. Heck, *Earthquakes*, Princeton University Press)

commonly of short duration. They last from a few seconds to somewhat over a minute. The great San Francisco earthquake of 1906 lasted between 40 and 50 seconds. The duration of a shock is very important because the destructive effects increase greatly with increase in length of duration. After an earthquake has taken place, secondary or after-shocks, commonly of lesser intensity, may follow intermittently for several months.

***Earthquake Intensities.*** Several classifications of earthquake intensity have been used. To the engineer, a classification based on the maximum acceleration of the ground is of most interest. Table 10.1 presents one of the commonly used intensity scales with the acceleration values inserted.

The acceleration due to gravity is 9800 millimeters per second each second. It should be remembered, however, that any one earthquake may have many different accelerations, and that different geological conditions give rise to different effects.

Instrumental records of earthquake vibrations are supplemented by information gathered from individuals through various types of questionnaires. Many data that are not brought out by instrumental methods are thus assembled; and information is gathered also from areas where no instruments have been established. These data may be approximately fitted into the classification of Table 10.1.

A specimen questionnaire is shown as Table 10.2.[3]

[3] From Heck, N. H., *Earthquakes*, Princeton University Press, Princeton, N. J., 1936, p. 53.

TABLE 10.1.* MODIFIED MERCALLI SCALE OF EARTHQUAKE INTENSITIES

| Intensity | Max. Acceleration mm/sec/sec | Remarks |
|---|---|---|
| I. Instrumental | < 10 | Detected only by instruments. |
| II. Very feeble | > 10 | Noted only by few people at rest. |
| III. Slight | > 25 | Felt by people at rest. Like passing of truck. |
| IV. Moderate | > 50 | Generally perceptible by people in motion. Loose objects disturbed. |
| V. Rather strong | > 100 | Many awakened, dishes broken, bells rung, pendulum clocks stopped. |
| VI. Strong | > 250 | Felt by all, some people frightened. Damage slight, some plaster cracked. |
| VII. Very strong | > 500 | Noticed by people in autos. Damage to poor construction. Alarm general. |
| VIII. Destructive | > 1000 | Destructive, chimneys fall. Much damage in substantial buildings. Heavy furniture overturned. |
| IX. Ruinous | > 2500 | Great damage in substantial structures. Ground cracked, pipes broken. |
| X. Disastrous | > 5000 | Many buildings destroyed. |
| XI. Very disastrous | > 7500 | Few structures left standing. |
| XII. Catastrophic | > 9800 | Total destruction. |

* Modified from Holmes.

TABLE 10.2. SPECIMEN QUESTIONNAIRE

AN EARTHQUAKE WAS FELT, NOT FELT, ON

Date Time a.m. p.m.

Please return the card even if the shock was not felt, as such information is essential.

Place

Shook how long

Please underline the words below which best describe the shock at your locality.

Felt by few, several, many, all, by observer, by others.

In building, wood, brick strongly, weakly built; on 1, 2, floor, lying down, sitting quiet, active.

Outdoors, by observer, by others; quiet, active

Direction of motion felt outdoors: N., N.E., E., etc.

Ground underneath locality: Rock, soil, loose, compact, marshy, filled in ; level, sloping, steep.

Motion rapid, slow, ; beginning gradual, abrupt.

Rattling of windows, doors, dishes,

Creaking of walls, frame,

Hanging objects, doors, etc., did, did not, swing, N., N.E., etc.

Pendulum clocks did, did not, stop, clocks faced N., N.E., etc.

Moved small objects, furnishings,

Overturned vases, etc., small objects, furniture,

Spilled water, oil, etc., from indoor, outdoor containers, tanks, etc. , in N., N.E., E., direction.

Cracked plaster, windows, walls, chimneys, ground.

Fall of knick-knacks, books, pictures, plaster, walls.

Broke dishes, windows, furniture,

Twisting, fall, of chimneys, columns, monuments.

Damage, none, slight, considerable, great, total in wood, masonry, concrete,

Awakened no one, few, many, all.

Frightened no one, few, many, all.

Trees, bushes shaken slightly, moderately, strongly.

REMARKS:

Signature .

Address ........................

Any additional information will be appreciated.

### Engineering Aspects of Earthquakes

Apart from landslides started by quakes and seismically generated water waves, the failures of man-made structures are responsible for most of the loss of life in earthquakes. Investigation of earthquake resistant structures and research in quake-safe design constitute an inviting field for the civil engineer in which much remains to be accomplished.

It has been noted at many places at many times that buildings founded on deep alluvial deposits, "made" land, or on other unconsolidated materials suffer more severe shaking than similar structures founded on bedrock. In early September, 1944, an earthquake of an intensity of VII disturbed the Saint Lawrence River area (Massena-Cornwall) at the site of the proposed Saint Lawrence waterway development works. C. P. Berkey found it possible to correlate the destructive effects of the quake "with the geologic formations of the region, of which there are four types—(1) postglacial unconsolidated marine silts, which showed the most destructive effects; (2) glacial outwash and stream deposits next in disturbance; (3) glacial till and morainal deposits, with little or no damage; and (4) the rock floor of nearly flat-lying sedimentary formations, which were not sufficiently disturbed to cause damage to any local works." [4] Fox noted that during studies in Japan, ". . . it was found by experiment that in an excavation only 20 feet in depth the wave motion of the earth-tremor is very much less than it is at the surface." [5] In seismic areas, therefore, the cumulative experience of engineers indicates that, where possible, structures should be founded on bedrock. Where it is impossible to found the structure on ledge, "raft" foundations may be designed to allow the structure to ride out the disturbance. The Imperial Hotel, Tokyo, designed by the American architect Frank Lloyd Wright, was built with this type of foun-

[4] Berkey, C. P., "Engineering Implications of the Massena-Cornwall Earthquake," *Bull. Geol. Soc. America*, Vol. 58, 1947, p. 1167.

[5] Fox, C. S., *A Comprehensive Treatise on Engineering Geology*, 1935, p. 162.

dation and successfully withstood the great Japanese earthquake of 1923 that wrecked practically every other major structure in that city. The building was 500 by 300 feet at the base and stood seven stories high. Rather than attempting to reach bedrock by means of long piles, the architect called for a raft type of foundation, the upper stories were kept as light as possible, and the floors supported by cantilever girders. Lead conduits and mains were used which were laid in trenches beneath the building. Risers from the mains were through shafts, and the fixtures were as loosely coupled as possible.

It has been observed at many places that simple rigid structures have endured where more elaborate but poorer built buildings have failed. Heck[6] states, for example, that in the Charleston, South Carolina earthquake of 1886 which caused so much damage, a Negro family living in a log cabin in the violently disturbed area slept through the catastrophe. Well constructed, diagonally braced frame structures have stood up well. Brick buildings have been particularly hard hit in many earthquakes, perhaps because of inferior mortar work or because the walls were insufficiently tied together. Cracking in both brick and stone structures has been noted after many quakes. Among the taller structures, chimneys and stacks are particularly vulnerable. Omori gives the danger zone as between two- and four-fifths of the way up. Lower chimneys, also, are vulnerable and should be specially designed in seismic areas. In some areas of Italy, the height of buildings is restricted by ordinance to two or three stories. However, in San Francisco, well designed tall office buildings have withstood shock satisfactorily, and in Japan, likewise, tall structures, well founded and constructed, have survived. Japanese experience shows also that rigid construction is better than flexible construction. Footings are interconnected, columns cross braced, cross walls and partitions made rigid, and outside walls heavily reinforced so that structures may move or deflect as a unit. The

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[6] Heck, N. H., *op. cit.*, p. 195.

*upper parts are kept as light as possible, and in many localities a seismic factor .2 to .3 g is incorporated.*

The *seismic factor* in engineering design is comparable to the familiar design factor for wind-load assuming a steady or uniform load per square foot. Similarly, design for earthquake resistance incorporates a safety or seismic factor, i.e., a capacity to withstand horizontal forces in excess of normal requirements. In Japan, a seismic factor of 0.1 *g* is often taken; in other words, the structure is designed to withstand a horizontal force caused by an acceleration one tenth that due to gravity. Buildings with a seismic factor of 0.1 have survived earthquakes in which the acceleration was possibly as high as .5 *g*. Heck[7] explains this as possibly owing to the short time of maximum acceleration which did not permit the building to respond.

One of the important considerations in "quake-proofing" is resonance. Most engineering structures have a fundamental period related to resonance. The same is true for geological materials underlying the structure. Although various periods of vibration occur in any earthquake, the most frequently repeated are those characteristic of the material. If the characteristic period of the subsurface approximates that of the structure resting on it, the danger of failure increases. Where danger from resonance is determined, damping measures may be installed. Various methods for inducing vibration, both of geological foundations and man-built structures, have been developed in order to determine the fundamental periods.

In summary, experience has shown that rigid construction with a seismic safety factor, founded on bedrock, reduces the hazard of earthquake destruction.

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[7] *Ibid.*, p. 202.

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Geological Field Party in the Big Horn Mountains, Wyoming. (Courtesy Standard Oil Co., N. J.)

# CHAPTER XI

# GEOLOGIC FIELD WORK

GEOLOGIC REPORTS AND MAPS PRESUPPOSE FIELD WORK. Whether the engineer engages personally in the field work, acts as supervisor or director of a field investigation for some specific project, or evaluates or uses the work of others, it is essential that he know something of the methods by which geologic data are gathered and geologic surveying conducted.

Geologic mapping is a specialized type of surveying. In part the results are incorporated on maps; in part they are in the form of field notes. Every field area presents its own problems and consequently exactly the same procedures are not adapted to each. Some methods are excellent for large areas, other methods more suited to small areas. Some maps must be made in rough wooded territory; others must be made in flat open country. Besides the field conditions, the purpose of the survey is most important in choosing the method and scale of mapping. Some projects require large-scale maps accurate in minute detail; other projects require more ground coverage on a smaller scale, less exact in geologic detail. Ground-water studies, irrigation studies, or regional soil conservation programs call for quite different types of geological investigation than do proposed dam or building sites. In addition, time is a factor not to be ignored in any economic application of geology to practical problems. Practical geology is the most economical geology that yields the required data. The geologist, then, must be not only versatile, but well versed in field methods.

### Preparation for Field Work

Preparation for field work includes gathering such information as is available for the particular area of interest. For most engineering projects, sufficiently precise and detailed geologic information or maps are lacking. Clues to the type of geological conditions, however, can certainly be found, and for some areas considerable information is available. (See Appendix 1 for sources of geologic information.) Base maps must be assembled or made. Airplane photos or detailed maps or both are generally made in the preliminary stages of specific engineering projects. A reconnaissance of the area in question should precede actual field mapping. The reconnaissance assists in the choice of mapping procedures and instruments and should give an over-all insight into the geological problems to be solved. The preliminary reconnaissance should not be limited to the immediate site of the project but should include adjacent areas. The surrounding geology reveals important information not apparent in the project area itself. Most engineering projects, however, require certain, specific, and localized information for very limited areas; consequently inferences drawn from surrounding areas must always be verified.

### Methods of Gathering Data

There are a variety of systematic methods for gathering geologic data. Various instruments are used, and often several techniques are combined.

In areas of steeply dipping sedimentary and metamorphic rocks, horizontal control is more important than vertical control. Conversely, in areas of flat or gently dipping beds, elevations are correspondingly the more important. If a sufficiently accurate base map of suitable scale which has abundant readily spotted points that can be used for control is at hand, many locations can be made accurately without instrumental measurements. Cultural features are especially useful in establishing locations. Unfortunately, in many areas, locations established by reference to map features must be supplemented

by those established by horizontal and vertical measurements from some known reference point. Particularly is this true if accurate detail is required.

***Traverses.*** Geologic surveys are designed to gather data sufficient to prepare both plans and sections of the geology. In order to gather these data, field traverses are made according to some systematic plan. Three principal systems of traversing are (1) boundary tracing, (2) cross-structure traversing, and (3) multiple outcrop mapping.

*Boundary Tracing.* The margins of rock types are critical in mapping. By tracing the boundaries or contacts between rock types, a map delimiting the geologic units is compiled. At the margin of a formation or rock mass something has happened. An intrusive, for example, has forced aside, stoped into, brecciated, replaced, assimilated, or metamorphosed the host rock. Observations along the contact show most clearly what did happen as a result of the intrusion. Other types of contacts, also, are instructive and should be studied carefully in the field. In constructing geological plan or section, the location and attitude of the contacts must be determined or inferred. Actual tracing and mapping of contacts in the field, consequently, are general practice.

Unfortunately, outcrops showing the actual contacts of one rock type with another are limited, and many portions of the boundary must be interpolated between exposures of two rock types. The extension of observed boundaries may be aided by topographic relations. For example, a particular limestone may be weak and occupy valley bottoms or lowlands; a particular adjacent sandstone may be a resistant ridge-making rock. The boundary between the two may be reasonably inferred by the topography. Graphical methods may assist tracing boundaries if dip and strike are consistent. (A consideration of graphical method is found in Chapter XIV.) Variations in soil color and lithology frequently indicate the position of a concealed contact. Because so much of the length of contacts is concealed, boundary tracing is something of an art as well as a science; although inference and deduction assist, the art must be controlled by field traverses.

*Cross Structure Traverses.* In the areas of strongly folded sediments and metamorphics, the most information in the least time can be gathered by making traverses roughly at right angles to the prevailing structural trends. If the traverses are closely spaced, the boundaries between formations can be closely drawn. The majority of traverses in deformed regions are planned to cross structure.

*Multiple Outcrop Mapping.* If sufficient time is available or complete detail sought, all exposures within the map area are studied. The results, therefore, are the most complete possible without subsurface exploration and, if the latter is necessary, the locations where the supplementary information is needed and can be obtained become apparent. This method of multiple outcrop mapping is the method of most engineering geology surveys.

## The Instruments

The undergraduate engineer is especially familiar with the use of chain, Wye and Dumpy levels, and transit. His acquaintance with the plane table is frequently scant. Barometer and compass are familiar but for the most part unused tools. The emphasis is rightly on transit, level, and chain. Much geological surveying, however, is done with compass only. For some types of work the barometer is very useful, and most of the detail mapping is done with alidade and plane table or chain and compass. In underground work—mines and tunnels—a chain and compass are the usual tools. In this section, therefore, the compass, barometer, and alidade are briefly described, and their uses indicated. Manuals of higher surveying should be consulted for details of theory and use of these instruments.

***Geologist's Compass.*** A variety of compasses are used by geologists, but by far the majority of American geologists use the Brunton compass or so-called pocket transit. This compass is provided with a movable horizontal circle graduated in degrees either by quadrants or in azimuth. A screw sets off the proper declination by rotating the horizontal circle so that direct readings of true bearings may be made. Provided with folding sights, the Brunton can be used on a Jacob staff as any surveyor's compass. The lid has a mirror with

a medial line etched on it. Within the horizontal circle is mounted a bull's-eye level for leveling the compass and also a movable cylindrical spirit level operated from the back of the compass box by a lever and referenced to a protractor engraved on the inside bottom of the compass box. The compass can thus be used as a hand level or clinometer as well as a direction indicator. Inclinations can be read as angles or percentage of slope. The folding sights permit the use of the Brunton as an open-sight alidade, although it is not convenient for this purpose.

The principal uses of the compass are: to determine traverse course directions, to measure dip or inclination of inclined structures, and to determine strikes.

*Bearings.* In determining courses, the compass is held close to the body in both hands, with foresight arm extended, and the mirror lid so tilted that the line of sight and the compass box are simultaneously seen. Bearings are read from north and south. Thus an object bearing N 20° E lies along a line 20° east of north from the station. The bearings for traverse courses are the forward bearings, although it is frequently desirable to record also the reverse bearing. Precise reading of the compass needle of the Brunton is not possible, although with care the errors are slight. Customarily the swing of the needle is damped to a swing of ten or twelve degrees, by pressing the damping device, and the midpoint of several swings taken as the course bearing. The end of the compass box labeled NORTH is pointed in the direction of sight. If the north end of the needle is less than 90° from the north point on the graduated circle, the forward bearings are north bearings. If the north end of the needle is more than 90° from the north point of the graduated circle, readings are south bearings. *It is always the north end of the needle that is read.* To facilitate reading, bearings *east* and *west* are marked in what appears to be reversed positions within the compass box. This is because in sighting, the compass box is *turned about the needle,* which always points north. Thus by reading the degrees at the point of the needle, the angle between the compass needle and the axis of the compass is measured. It is the latter, the axis of the compass,

that lies in the line of sight. Hence, if the compass axis (direction line) is to the right of the needle, the direction is an easterly bearing line. The needle point is read against the graduated circle, however, and the needle point is to the left of the north point of the circle—hence the reversal of letters in the compass box. This point is illustrated in Fig. 11-1.

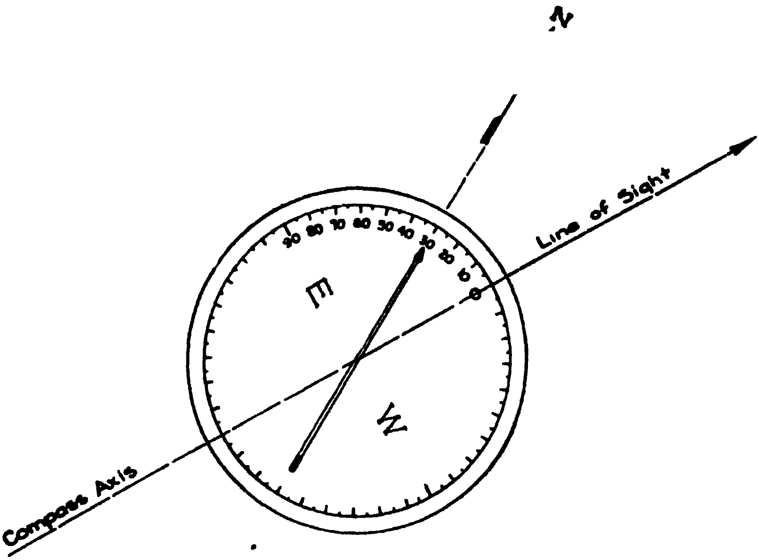


FIG. 11-1. Reversal of letters in compass box. The line of sight, compass axis, lies to the east of magnetic north. But the angle between the line of sight and magnetic north is read at the end of the compass needle; hence, for ready reference, the letters E and W are reversed in the compass box.

*Strike and Dip.* Strike has been defined as the *direction* of the line of intersection of a horizontal plane with the considered plane, or the direction of a level line drawn on the considered inclined plane. This direction is conveniently measured by leveling a compass against the surface whose strike is sought. The bull's-eye level is used for this operation. The bearing is then noted and recorded. Because most rock surfaces are irregular in detail, the compass is advisedly leveled against a hard-covered notebook placed flat against the outcrop surface to be measured. Another method is to level the compass and sight along the surface being measured.

Dip, defined as the maximum slope of a surface, is measured by laying the side edge of the compass box on the flat notebook surface against the rock—*the face of the compass lies in the vertical plane* at right angles to the strike. The bubble of the cylindrical spirit level is then brought to centered position by manipulating the lever arm on the back of the compass box. The angle of inclination is then read against the protractor. Another method is to sight along the compass edge and manipulate the spirit level as before.

It is often necessary, because of irregularities of a surface, to take the average of several readings if the compass is held directly against the rock, even with the notebook interposed. The sighting methods are therefore frequently superior, since minor bends or warps of the rock surface can be discounted in the sighting. An accuracy of 2°, plus or minus, is acceptable for dip and strike values.

*Other Uses.* The Brunton is also used as a hand level. The compass is tipped on edge, with sight arm extended and the peepsight on end of sight arm at right angles to the sight arm. The compass is then sighted by looking through the peepsight and through the hole in the mirror lid. The mirror lid is closed to a position such that the reflection of the cylindrical spirit level and its protractor is conveniently viewed. The spirit level is then manipulated into horizontal position and the slope angle read, just as with the Abney level. If the level arm is set at 0° against the protractor, the Brunton can then be used as a Locke hand level.

The Brunton is a simple, compact, and sturdy instrument, useful in a variety of ways, and is superior to any other compass for most geological purposes. Even competent surveyors, however, need some practice in its use.

***Barometer.*** The aneroid barometer is a portable instrument designed to weigh or measure air pressure. It is a delicate device, easily thrown out of adjustment, and its use entails labor-adding corrections. However, it is the only easily portable, one-man tool for elevation determinations; improvements have made it quite reliable; and readings are quickly and easily made. For details of

barometric surveying, reference should be made to texts of higher surveying.[1]

The barometer is best adapted to a terrain of moderate to high relief. The accuracy of a barometer is less near the limits of its registration; hence if elevations are 4000 feet or less, a barometer registering up to 5000 feet is satisfactory and better suited to the terrain than one registering up to 10,000 or more feet.

If temperature and air pressure were constant, differences in elevation could be read directly from changes in pressure as the instrument was moved up or down. Temperature changes do affect the results, however, and a temperature correction is sometimes necessary if the change amounts to more than a few degrees between stations. Atmospheric pressures fluctuate more or less regularly every day and are subject also to irregular and sometimes rapid changes. It is necessary therefore either to check the readings at control points frequently during the day's work or to have recordings made at regular intervals on a second barometer left at base camp so that a correction curve can be constructed. A barograph (self-recording barometer) is most convenient. With the control readings of atmospheric pressure changes recorded at a constant elevation, the readings for near-by stations can be corrected. However, one barometer only is frequently used. One method of checking atmospheric pressure changes is to take two readings at each station, one on arrival, and another on departure. Thus if the stations are fairly close together, fluctuations of air pressure can be plotted at least roughly.

In conjunction with a compass, the barometer greatly aids in establishing the location of an outcrop in hill or mountain country. If a compass bearing can be taken on some identifiable map feature and the contour established by barometer, the location is quick and accurate. The more nearly at right angles to the trend of the contour the compass bearing is, the more accurate the fix. Two or more compass bearings can be used without the barometer for the same purpose, but in wooded terrain it is frequently difficult to pick out

[1] A practical and accurate discussion of the barometer may be obtained from the American Paulin System, 1220 Maple Avenue, Los Angeles, California.

two properly placed landmarks. In rough country, the course bearings of a compass traverse are accurate, but distance determinations by pacing are difficult or impossible. Barometric elevation determinations help in the locations. The barometer thus assists in horizontal as well as vertical determinations. For rapid surveys, where elevations accurate within 10 feet or less are acceptable, barometric leveling is convenient and rapid.

***Alidades.*** Alidades, used with the plane table, are of two types: sight and telescopic. The former is simply a ruler fitted with folding sights. The ruler is usually a flat metal strip with a graduated, beveled edge. The folding sights should be long enough to permit slope sights. With a 10-inch base the sights, therefore, should be 3 to 4 inches high. The sight alidade can be used without a field assistant and is capable of producing results of a high degree of accuracy. Elevation differences, if required, can be established with hand level or barometer. When mapping on a previously prepared base, with oriented table, locations can be made quickly and accurately by resection. The principal advantage of the instrument is that it can be used without a field assistant; its chief disadvantages are the lack of vertical control, and the necessity of carrying a traverse table.

The telescopic alidades in use by geologists are principally of the exploration or lightweight types. Horizontal and vertical differences between stations are by stadia, hence the minimum party consists of a geologist-rodman and an instrument man. The geologist takes the rod, for he must determine where the locations are to be made and examine the outcrops mapped. The instrument is best adapted to detailed surveys in relatively open country. The techniques of topographical mapping by use of the plane table and telescopic alidade, supplementing photographic surveys, have been brought to a high level of speed and efficiency by American topographical engineers.

Most civil engineers, probably because of greater familarity with the transit, will choose that instrument when confronted with a mapping job. If transit and stadia rod are used in preference to the alidade, there is little opportunity for sketching in the field, and it

is necessary to locate many more points with the pious hope that office interpolation will be sufficiently correct. Good field notes for topographical surveying with the transit require a higher degree of skill and judgment than almost any other kind of surveying. No reasonable amount of written notes or notebook sketches can be worked up in the office to produce as accurate a topographic map as it is possible to make in the field with the plane table. In the winter and spring of 1942, several parties were engaged in making topographic maps of six federal housing projects in the same area. One group using the plane table and alidade performed its work at a unit cost of $4.50 per acre, which included necessary horizontal and vertical control and delivery of a pencil copy of the map sheet. The unit costs of the transit survey groups ranged, under the same conditions, from $15 to $30 per acre.

***Transit.*** In detailed surveys, especially in heavily wooded country, it is frequently advantageous to establish a network of control points with the transit. Subsequent geological observations can be tied to these points by pacing, chaining, or by plane table. The transit is used to advantage also in underground work, as in tunnels or mines.

## Field Procedures

Geological data are assembled in map form by the use of the instruments mentioned, supplemented as occasion demands. The choice of methods and instruments is dependent on terrain, objectives, time and manpower available, and upon the type of base map obtainable. Much geological mapping is done on the topographic maps of the U. S. Geological Survey. These may be blown up to larger scale but seldom are satisfactory when enlargement is more than three times original scale. Aerial photographs are currently much used, and for many purposes are highly satisfactory. Information on available photographs for United States areas can be obtained from the Map Information Service, U. S. Geological Survey, Washington 25, D.C. The survey procedures most commonly

used are: pace and compass, chain and compass, barometer, and plane table and alidade traverses.

***Pace and Compass Traverses.*** In the pace and compass method, horizontal distances from known points are determined by pacing along compass courses. With practice and in country not too broken or too thickly overgrown, surprisingly accurate traverses can be run. The pace length should be determined by periodically pacing measured distances under field conditions. Many "standardize" their pace in up and down country and make no pace corrections for slope. Because most traverses are closed, as much "down" as "up" is covered; hence plotting the average pace uncorrected for slope is satisfactory. An ordinary walking step should be used. Every other step or every fourth step is counted, sometimes mentally, sometimes with a mechanical counter. If counting mentally, each hundred can be marked by picking up a pebble, blade of grass, or leaf.

A compass traverse should be closed, i e, it should begin and end at known points. The traverse may finish at its starting point or at some other known point. A convenient form used for recording a pace and compass traverse is shown in the following field notes:

*Traverse started at* .. . .....

| *Direction* | *Distance* | # | |
|---|---|---|---|
| S10°W | 160′ | 1 | *Otcrp.* Fine text. bio. gn. gr. cut by crs. bio. peg. Foliation of gn. gr. N60°E. vertical. |
| S60W | 70′ | – | Birch tree |
| S70W | 52′ | 2 | *Otcrp.* small plunging anticline. 28° Greenish quartzite(?) (spec. 28-2) 58° cut by red-weathering gn. gr. 50° |

*Traverse Ended at* ..........

The outcrop notes can be described by number on the facing page of the notebook. In running compass traverses, short sights are preferable to long shots. If the traverse fails to close, either bearings

or distances or both are in error. It is customary to distribute the error, assuming it to have been cumulative, according to the following scheme illustrated in Fig. 11-2. A "closure" ($AA_1$) line is drawn, and divided into as many equal parts as there are stations on the traverse minus one. Lines parallel to the "closure" line are drawn

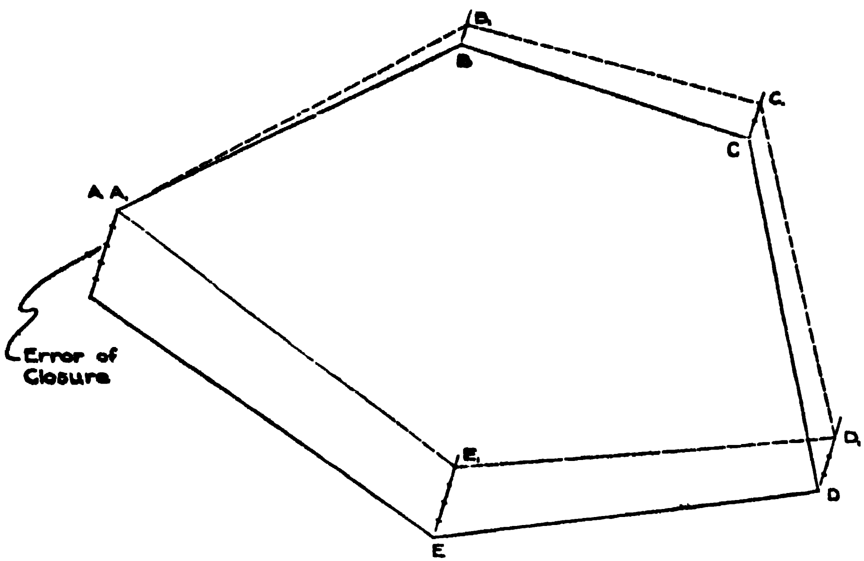


FIG. 11-2. One method of error distribution in adjusting a traverse.

through each station, excepting the initial one (A). The last station on the traverse must be corrected the whole amount of the failure to close. The next to the last must be corrected by its proportional part, and similarly each other station. In the diagram the total number of stations is six. The "closure" line ($AA_1$) is therefore divided into five parts; station 5 must be corrected along the correction line four-fifths of the failure to close, i.e., four-fifths of $AA_1$. The other stations are corrected in the same way. There are more accurate methods, but their use is not often warranted.

The pace and compass traverse is especially useful where control points are numerous, but the visibility between them is poor. Although it is an approximate method, the accuracy is surprisingly

good. The engineer is prone to scorn the human legs as surveying instruments. However, many pace traverses have an accuracy of 1:100 to 1:50.

***Chain and Compass Traverses.*** The chain and compass method simply substitutes chaining for pacing in establishing distances. The method is most conveniently used with an assistant to aid in handling the tape. The geologist frequently works alone, however, fastening one end of the tape by means of a spike driven into a rock crevice, or anchoring it. Chain and compass mapping is perhaps most frequently used in surveying mines, mine prospects, or detailing large exposures of particular interest. In conjunction with pace traversing, chain control may be used effectively. Errors in measurements by steel tape should be on the order 1:2000 or less. Compass bearings therefore, are the major cause of error in this method. Conversion of slope measurements to horizontal distances should be made if the slope angle is more than six or eight degrees; but refinements of chain correction, required in precise surveying, are not warranted in geological mapping.

***Barometer-Compass Traverses.*** In regions of moderate to high relief, the barometer can be effectively used in conjunction with the compass in traversing. The use of altitudes in helping to fix positions when a contoured base map is available has already been mentioned. Barometer traverses may be plotted in the field notebook together with geologic data as the traverse progresses. The result of this method of graphic note-taking is a geologic profile.[2] As in all geologic profiles, the vertical and horizontal scales should be the same. Because barometric readings must be corrected, many prefer to tabulate the traverse data as it accumulates, thus:

| LEFT HAND PAGE | | | | | RIGHT HAND PAGE |
|---|---|---|---|---|---|
| *Station* | *Bearing of Last Station* | *Distance* | *Time* | *Barometer* | *Geologic Notes and station descriptions go on this page.* |
| | | | | | |

[2] Lahee, F. H., "The Barometric Method of Geologic Surveying for Petroleum Mapping," *Econ. Geol.,* Vol. 15, 1920, pp 150 169.

*Notes corresponding to station numbers are on the facing and following pages of the notebook.*

*Careful work with a good barometer should give errors of less than one foot vertical in a thousand feet horizontal.*

***Plane Table Traverses.*** Plane table traverses can be run with a sight alidade and a lightweight traverse table without assistance. A base line is laid out with a steel tape at the start and plotted on the sheet according to a chosen scale. From a set-up at one end of the base line, sights are taken to prominent landmarks, outcrops, and other features desirable to locate, and rays drawn on the map. These are numbered on the map sheet, and perhaps with chalk on the object sighted, as for example on the outcrop. The table is then moved to the other end of the base line and oriented by backsight. Rays sighted to the same objects as previously fix a number of locations by intersection. Further triangulation expands the map. The table is easily located on new set-ups by resection. The familiar three-point problem is usually to be solved in these determinations.

The traverse table-sight alidade method is frequently combined with pace measurements; in this usage, the table is oriented by compass, rays drawn to points wanted on the map, and the distances paced. In some work the steel tape is used. If desired, contours can be put in by hand-level or barometer. When elevations are to be mapped, however, the telescopic alidade should be chosen.

The advantages of sight alidade-plane table traversing are the lightweight equipment, relative speed, good accuracy, and non-necessity of an assistant. The method is intermediate between pace and compass and chain and compass methods. The disadvantages are lack of vertical control and the necessity of carrying a traverse table. The latter is at least partially offset by the convenience of plotting the traverse as work proceeds. The author has seen a light traverse table carried in the field solely for plotting pace and compass traverses.

The telescopic alidade and plane table are most frequently used in mapping details over an area of moderate size. For small areas the chain and compass method is used; for large areas, pace and

compass. In particular, the telescopic alidade is used when vertical determinations are of importance, as in areas of low-dipping rocks, where dip and strike cannot be determined by compass but must be determined from the elevations at top or bottom of some key bed. Hence, much use is made of this equipment in the exploratory mapping for oil structures. If the topography has not been satisfactorily mapped previous to the geological survey, it may be necessary to map both geology and topography to solve geologic structure. For combined topographic and geologic mapping the telescopic alidade and plane table are the best instruments to use. Ordinarily, however, it is not convenient to carry on the two surveys simultaneously. If it is necessary to map both topography and geology during the same survey, an extra rodman for topography permits the geologist-rodman to concentrate on the geology.

Stadia locations by radiation are abundantly made. Quarries, for example, can frequently be mapped from one or two favorable setups. Locations can also be made by resection and intersection as well as by stadia measurement. If cutting in by resection, the three-point problem usually has to be solved. One of the quickest and easiest ways (for most cases) to solve it is to orient by compass and establish a triangle of error. The drawing board can then be rotated slightly, and a second triangle of error established by sighting on the same three points. The intersection of the lines connecting the corresponding angles of the two triangles gives the desired point, which can be used to reorient the board exactly. For the reduction of angle shots, many find the Beaman arc advantageous, although most undergraduate civil engineers are not familiar with its use.

Stadia measurements should be accurate to 1 foot in 400 for horizontal distances, and an error of more than 3 feet should not accumulate for vertical determinations even in long traverses.

## Field Records

Maps and notebooks constitute the field records. The two are supplementary and both are made in the field. Memory is unreliable and is no substitute for field records. Field notes should be kept

neat and legible, and all abbreviations should be self-explanatory. It goes without saying that field notes should be intelligible to others as well as to the maker. Because notes must be keyed to maps by some system of reference, the method employed should be explained in the front of each notebook, even though the same system is employed for all field work.

***Notebooks.*** The styles of notebooks vary, but stiff covers are preferable to floppy ones, and cross-section paper is more convenient than blank or lined paper. If the pages are detachable, they may be filed, but if they are not detachable an index should be made for each notebook.

Various systems of map reference are used. If the region is divided into sections, the township, range, and section division serve as notebook locations. If the country is not sectioned, and the standard topographic quadrangle is used as a base, each of the nine rectangles can be numbered. By ruling each rectangle into half-inch squares, a coordinate system of letters and numbers gives convenient means of location, thus: Bucksport II, A 1 NW; II means the north central rectangle of the Bucksport Quadrangle, A 1 means the northwesternmost half-inch square of that rectangle, and NW means the northwestern quarter of that square. A celluloid coordinate sheet, cut to rectangle sizes, saves ruling each map. Every note should be headed with a precise location.

Field notes cannot be too full. Six months or six years after they have been taken, the details may be lost to memory, and it is generally economically impossible to return to the area or to a specific exposure for review. Numerous notebook sketches are of invaluable assistance as are also photographs.

Geological observations to be made are:

*Lithology*

Rock type and mode of occurrence, as veins, dikes, beds, lenses, etc., and sequence and thickness where observable.

Grain size, color, mineralogical make-up.

*Structure*

Primary structures, as ripple mark, cross-bedding, stratification, lamination, flow structure, etc.

Secondary structures and their attitudes, as dip and strike of beds, axial planes, axes, lineations, cleavages, fractures, etc.

*Metamorphism*

Kind and degree of alteration and the alteration products.

*Topography*

Forms and kinds, agents responsible for, and relations to bed rock.

*Miscellaneous observations*

Individual for any particular exposure.

*Remarks*

Such as interpretations, tentative correlations, ideas, questions, possibilities, etc.

The schedule suggested is not by any means complete and for each particular job should be modified to include pertinent observations; it is intended to be suggestive only. Observation is the keynote of success in field mapping. Good mapping depends on good observation, accurate location of the points where observations were made, an accurate record of observations, and correct interpretations of the observations. *The facts of observation should be clearly separated in the field records from inference and hypothesis.*

In brief: locations for each notation must be entered, and the notes themselves must be clear, legible, and complete; in addition, the more and better the notebook sketches and diagrams, the clearer the notes.

***Maps.*** Locations on the base map used or constructed should be precise up to the limits of scale. An error of 50 feet on a scale of 1:62,500 might be the width of an ordinary pencil line, but on a scale of 1:600 it would be an inch. Elevations should be within half the contour interval of the map.

On the map are entered symbols for dip and strike of beds,

cleavage, joints and faults, and arrows for linear features such as fold axes. The conventional symbols are shown on page 293. Symbols or colors—usually colors on field maps—are used for the different rock units mapped. In addition to structural data and lithology, notations are frequently entered on the map or its margins. In large-scale mapping, the shapes of the outcrops are usually drawn. It is seldom worth while to take great pains in accurately outlining the exposure, however, because the outlines and area exposed depend merely on the accidents of sod and soil cover.

***Samples.*** Samples are taken in the field for laboratory study and as representatives of the formations mapped. The note record should indicate where the samples were taken and what they represent, and it should give the sample number. Rock samples for geological study are commonly about 3″ × 4″ × 1″, and can be collected in paper bags on which the number can be written in several places, or in cloth bags with data inclosed. Samples for engineering tests must be larger, and the sampling technique must be suited to the purpose of the sampling.

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# CHAPTER XII

# GEOPHYSICAL EXPLORATION IN ENGINEERING

IN REGIONS OF MANY OUTCROPS, WHERE THE STRATIGRAPHIC sequence and structure can be determined satisfactorily from surface exposures, there is little need of subsurface exploration. In other regions, however, especially those of few outcrops and slight relief, supplementary information is essential. The engineer requires specific and detailed information on local conditions. Although a regional history and a satisfactory concept of regional structure may be obtained from surface observations, the necessity for thorough exploration of the materials in which or on which engineering construction is to be undertaken is so apparent as to need little comment. Intelligent design and safe, economical construction require thorough appreciation of subsurface conditions. The objectives of subsurface exploration are, consequently, quantitative data on the kinds, properties, amounts, distributions, and structure of the material under and adjacent to a proposed structure. Two groups of methods are available whereby these data may be gathered. The first of these groups involves direct penetration of the materials. This is possible by means of various types of drills. The second group of methods involves making and interpreting certain physical measurements from the surface without direct penetration. The two approaches are not mutually exclusive, and in practice generally are combined with excellent results. This chapter is concerned with the indirect, geophysical, methods of subsurface exploration. This discussion is not a technical treatise on the tech-

niques of subsurface exploration; the aim is to direct attention to geophysical methods and their applications to engineering problems.

## GEOPHYSICAL METHODS

Geophysical exploration consists of measuring, from the surface, certain physical properties of the underlying material, and of interpreting the measurements in terms of geological structure and lithology. It is emphasized at the start that the data of geophysical measurements are valuable to the engineer only when correctly interpreted in geological terms. The properties investigated by the physical measurements are density, elasticity, electrical conductivity, and magnetism. Divination, as practiced by "water witches" (dousers) and some mineral prospectors, makes no measurements, furnishes no quantitative data, and is not a geophysical method. Its practice and use are left to those of mystic mind, credulous ignorance, and with faith in the occult.

The four principal methods of geophysical exploration are: gravitational, magnetic, seismic, and electrical. Of these, seismic and electrical methods have the widest range of application in civil engineering practice.

***Gravitational Methods.*** Differences in densities of adjacent rock masses give rise to measurable differences of gravitation. In its outer part at least, the earth is not homogeneous. Hence gravitational measurements often make possible the establishment of boundaries between masses of different density.

Because the earth is a rotating body, slightly flattened at the poles, gravity values vary with latitude. These values also vary according to terrain and elevation. Corrections must therefore be applied to reduce the observed values to a common basis. In reducing observed values to sea level, the influence of rock masses between sea level and the elevation of the station is taken into account. Anomalies of gravity, i.e., the differences between the theoretical and the corrected, observed values, are represented in plan by contours of equal gravity anomaly values, called *isogams,* and in section by anomaly profiles.

*The Instruments.* Two types of instrument, pendulums and gravimeters, are used in making direct measurements of gravity values. In pendulum instruments, the period of oscillation is affected by gravity changes. The pendulum method is slow and not adapted to ordinary engineering surveys. Gravimeters are instruments designed to compare gravity with the elastic force of springs or wire suspensions. The displacements are magnified electrically or optically. A third type of instrument, the torsion balance, is used to determine relative values. A torsion balance consists of a beam suspended from a vertical wire. Beams of various designs with ends

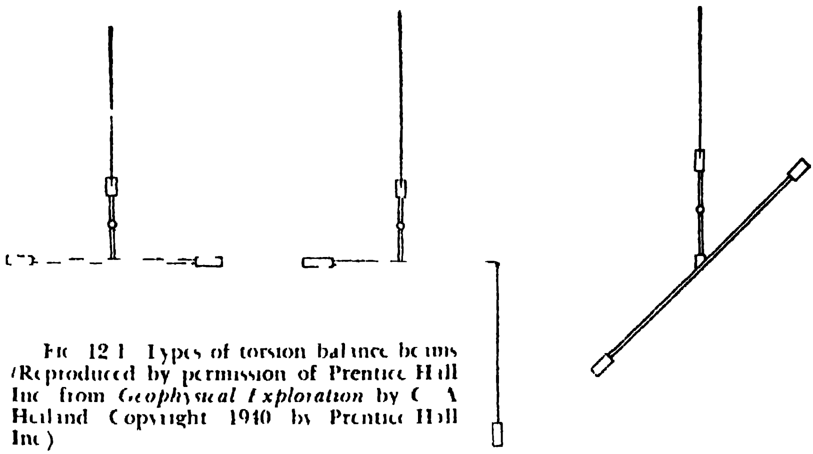

Fig. 12.1. Types of torsion balance beams. (Reproduced by permission of Prentice-Hall, Inc., from *Geophysical Exploration* by C. A. Heiland. Copyright 1940 by Prentice-Hall, Inc.)

weighted are used. To increase sensitivity, the weight on one end may be suspended or the beam tilted. Three types of beam in use are illustrated in Fig. 12.1. In areas where gravity varies from place to place, the beam is deflected from the torsionless position of the suspension wire to a position determined by the unbalanced horizontal components acting on it and on the masses at either end.

The results of gravitational surveys may be plotted to show the horizontal gradients of gravity value or the deviation of the equipotential surface from spherical. The Fotvos unit, which is $1 \times 10^{-9}$ dyne per horizontal centimeter, is used to express the gradient values. The horizontal gradients determined are the result of sub-

*surface differences in density. Thus where differences in densities of adjacent rock masses at the same level are greatest, the steepest* gradients appear on the plat. The gradients are shown on maps by arrows proportional in length to the Eötvös units. A map presenting the results of a torsion-balance survey is shown in Fig. 12-2.

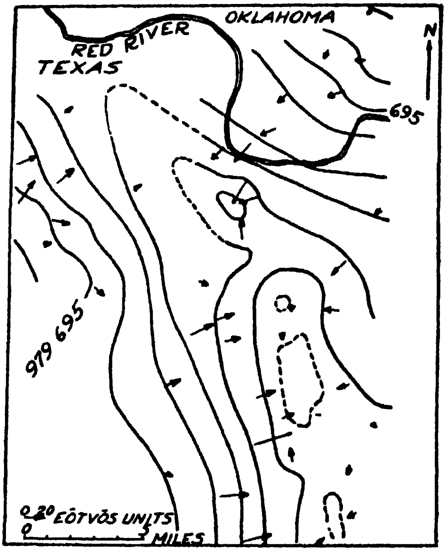


FIG. 12-2. Results of a torsion balance survey over a buried ridge of metamorphic rocks. (After D. C. Barton, courtesy of the A.I.M.E.)

The values determined by the torsion balance are relative only; however, if the absolute value for one station has been determined, the data may be adjusted, and a contour, or isogamic, map constructed. The presence of faults may be indicated by sudden changes in gradient. One example is shown by Fig. 12-3, in which the gradient profile and geological section show the clearly defined relationship. The configuration of crystalline rock surfaces buried by sediments has been successfully mapped by this method.

*Engineering Application.* The principal use of the gravitational methods has been by petroleum engineers engaged in subsurface exploration. The outlining of anticlinal structures, buried ridges,

*and intrusions, and the determination of faults and major subsurface* structural trends constitute the major applications in the field. To a lesser extent, mining geologists have utilized gravitational methods in outlining ore-bearing bodies and structures. The investigation of

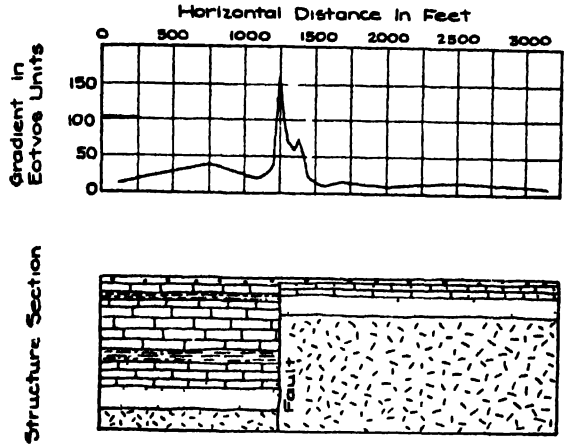


FIG 12 3 Determination of fault by torsion balance survey (Reproduced by permission of Prentice Hall, Inc from *Structural Geology* by Marland Billings Copyright, 1942, by Prentice Hall, Inc)

buried channels has also been carried out. Gravitational surveys, however, at present are of limited use in the practice of civil engineering.

## MAGNETIC METHODS

Rocks not only vary in density but also in magnetism. Hence, just as gravitational anomalies may be discovered and represented on maps, magnetic anomalies may be determined and used as a basis for interpretation for subsurface conditions.

The earth itself is a giant magnet, with poles far below the surface. The projections of its magnetic poles are near but not coincident with the poles of the axis of rotation. The magnetic force lines of the earth are shown diagrammatically in cross-section in Fig. 12-4. A magnetic needle freely suspended will take a definite position in space, depending on the lines of magnetic force of the

earth's field at that place and time. A needle perfectly balanced on a vertical axis before it is magnetized will not remain in horizontal position after magnetism except at points on the magnetic equator. *North of this equator the needle inclines to the north; the inclination steepens with increasing distances from the magnetic equator.*

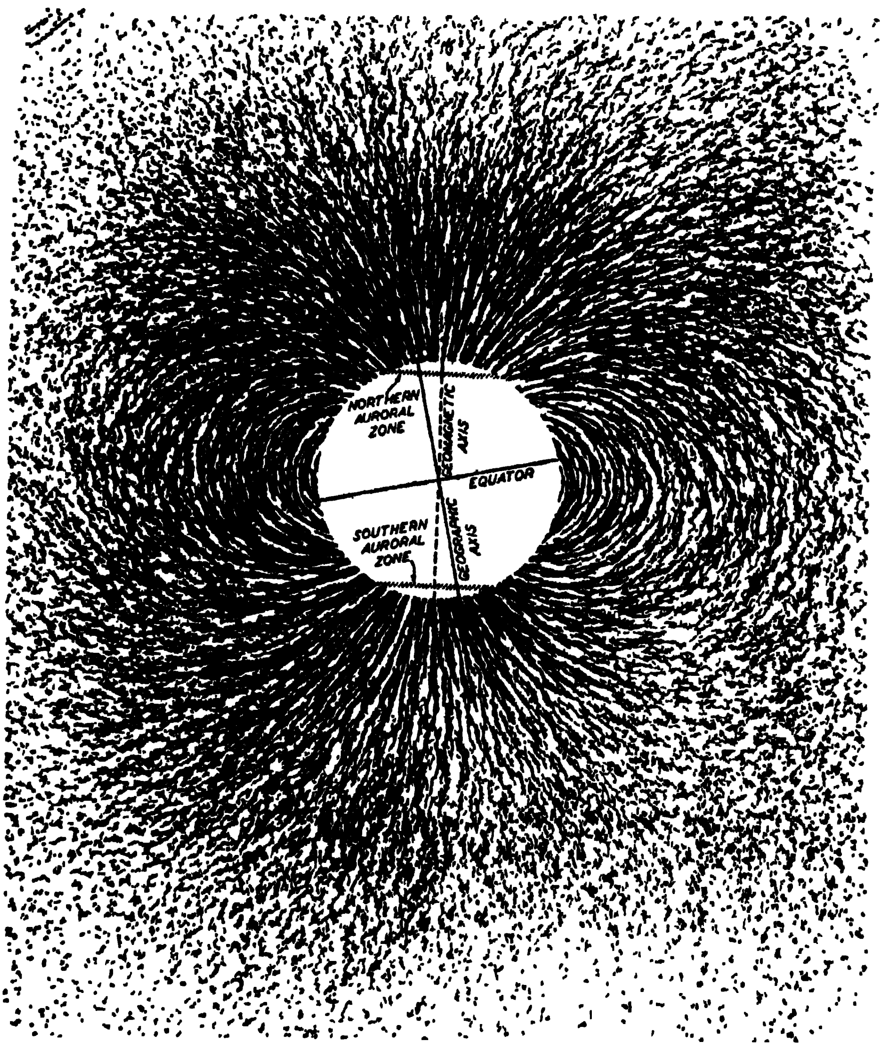


FIG. 12 4. The earth's magnetic field (Courtesy of the Carnegie Institution of Washington)

and the needle will be perpendicular to the earth's surface directly over the magnetic pole. In the southern magnetic hemisphere the dip of the needle is reversed. A counterweight, commonly a silver or brass wire, is adjusted to balance the needle in a horizontal position. The direction assumed by the balanced needle defines the magnetic meridian, and the angle which the magnetic meridian makes with the true meridian at that place is the declination. The declination at any given place, however, is not constant. Long time

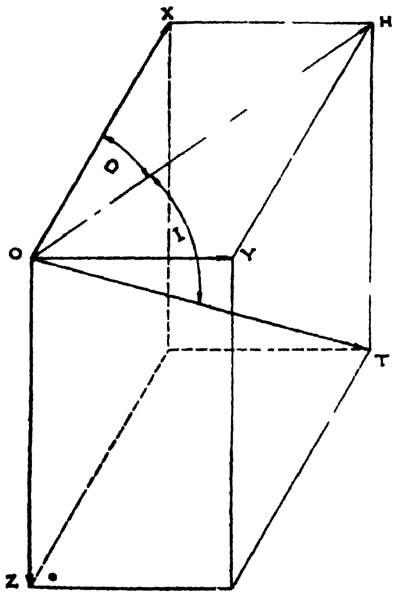


FIG. 12.5 Vector diagram of the earth's magnetic field for the Northern Hemisphere

X—north component
Y—east component
Z—vertical component
H—horizontal intensity
T—total intensity
D—declination
I—inclination

(Reproduced by permission of Prentice Hall, Inc. from *Geophysical Exploration* by C. A. Heiland. Copyright, 1940, by Prentice-Hall, Inc.)

(secular) changes and annual, daily, and irregular variations are recognized. Annual changes in declination are small, on the order of one minute. Daily fluctuations are on the order of 3 to 12 minutes; and irregular changes, magnetic storms, often give variations which in the United States, may amount to 10 or 20 minutes. Because of the variations in declination it is necessary to establish control in magnetic work just as in barometric surveying.

"The magnetic field of the earth and of geological bodies is uniquely defined by the magnitude and direction of the total intensity vector. In practice it is preferable to resolve the field into

its components which, in the direction of the vector, are the *horizontal* and *vertical* intensities."[1] The vector diagram for the northern hemisphere is shown in Fig. 12-5. In the diagram, $T$ is the intensity, $H$ and $Z$ the horizontal and vertical components, $D$ the declination, and $I$ the inclination or magnetic dip. $X$ and $Y$ are the north and east components, respectively.

In magnetic measurements, the unit is the *gauss,* which by definition is numerically equal to 1 dyne. In expressing magnetic

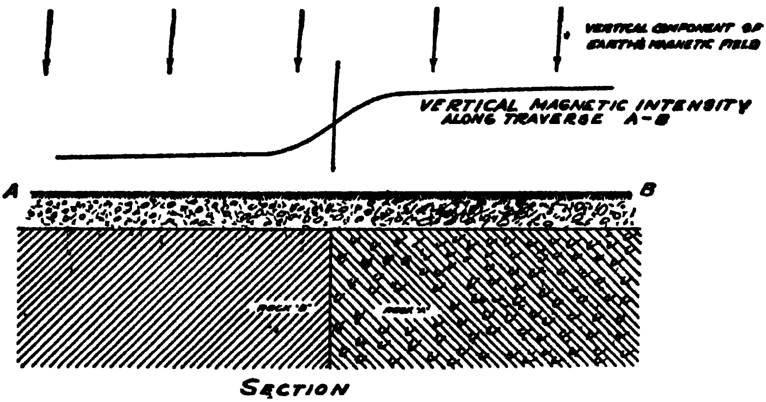


FIG. 12-6. Change in vertical intensity of earth's magnetic field caused by contact between two kinds of rock (After L. B. Schlicter, courtesy of the A.I.M.E.)

anomalies, the gamma ($1\ \gamma = 1 \times 10^{-5}$ gauss) is commonly used. For each station the theoretical intensities are compared with the observed intensities. The difference between the theoretical and observed intensities is the magnetic anomaly. The anomalies are plotted on maps, and contours (*isonomaly lines*) show magnetic conditions. Magnetic profiles are also used to portray magnetic values.

Because rocks are not homogeneous in magnetic properties but vary from place to place (Figs. 12-6 and 12-7), magnetic observations are significant. Every experienced surveyor is familiar with local anomalies which invalidate compass readings. Aside from the

[1] Heiland, C. A., *Geophysical Exploration,* Prentice-Hall, New York, 1940, p. 295.

familiar compass deflections caused by fences, cars, powerlines, etc., variations are due to the magnetic properties of the subsurface rocks. The most common magnetic minerals are magnetite and pyrrhotite. Both minerals are widely distributed. A few other minerals have similar, though weaker magnetic properties. Generally speaking, magnetic minerals are more abundant in the igneous rocks than in sediments. Magnetite and pyrrhotite are more abundant in basic rocks than in acid rocks. Magnetic minerals are frequently concentrated in the contact zones of igneous intrusions or in fault zones. In a sequence of sedimentary beds some generally have a greater degree of magnetism than others. Besides a content of magnetic minerals, there are other causes of magnetic variations. The bare ledges of mountains frequently have been affected by lightning to a marked degree. It is well established that mechanical stresses, such as those involved in mountain making, are also factors of magnetism.

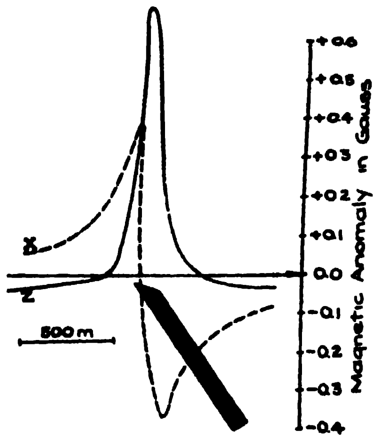


FIG 12 7. Magnetic anomaly caused by magnetite ore body at Kiruna, Sweden (From *Geophysical Exploration*, by C A Heiland, after Carlheim Gyllenskold)

*Instruments.* Three varieties of instruments are in common use. These are the dip needle, the Hotchkiss Superdip, and the magnetometer. The *dip needle* consists simply of a magnetized needle mounted on a horizontal axis. This is suspended from the hand and swung into the magnetic meridian, and the angle of dip or inclination is read. The Hotchkiss Superdip[2] is a refinement of the simple dip needle and is designed primarily for measurements of the total intensity. A nonmagnetic bar with counterweight is fastened to the needle. The centers of gravity of both needle and the counterarm are as nearly coincident with the axis of rotation as possible. The

[2] Stearn, N. H., "Geophysical Prospecting." *Am. Inst Min. and Met. Engrs.*, 1932, pp 169-186.

angle between the counterarm and the needle is adjustable and determines the sensitivity. The position of the counterweights on the counterarm changes the "latitude" adjustment. A thermometer is provided inside the case, and the whole is mounted on a tripod with a leveling head. The instrument is shown diagrammatically in Fig. 12-8. For rapid surveys, this is a reliable and accurate instrument.

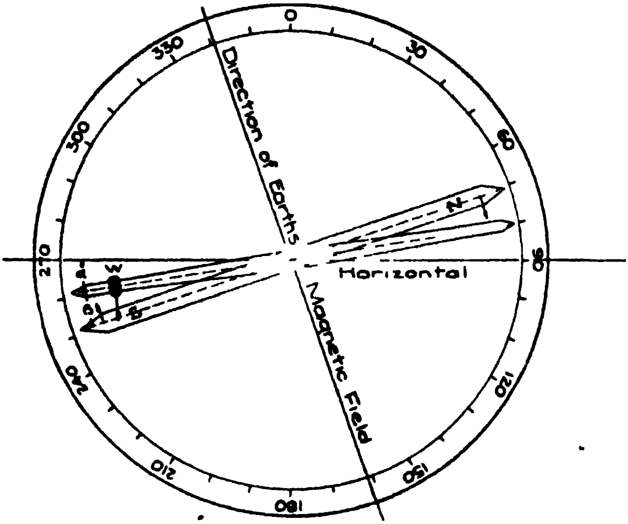


FIG. 12 8 Principle of the Hotchkiss Superdip (Courtesy of the Canadian Dept of Mines and Resources)

Instruments of greater refinement and more complex design are widely used in both prospecting and regional surveys. Of these the Schmidt vertical magnetometer might be mentioned, in which the magnetic system is balanced on a knife edge, at right angles to the magnetic meridian, and the Schmidt horizontal magnetometer, in which the magnetic system is parallel to the magnetic meridian. For further discussions of modern magnetic variometers and their use, the interested reader is referred to the bibliography at the end of the chapter. Rapid magnetic surveys by airborne magnetometers have been made successfully in several regions, and this type of survey is widely used in regional mineral reconnaissance.

*Engineering Applications.* Both oil and mining explorations have made wide use of magnetic explorations. In fact, more than a million square miles of the United States have been covered by magnetic surveys. Magnetic ore bodies are readily detected. Also, economic minerals, which are not themselves susceptible to magnetic location, may be associated with, or related to, magnetic minerals in such a way as to make magnetic surveys of value. At places, faults which bring together rocks of different magnetic properties may be inferred from magnetic data as may also folds which alter the elevations of magnetic beds.

In civil engineering the applications of magnetic methods are somewhat restricted. A few water supply studies have made use of magnetic exploration methods; igneous dikes, or faults, for example, locally form subsurface dams. At one place a magnetic survey of a basalt quarried for construction material served to distinguish areas underlain by sound basalt from areas underlain by rotten basalt. The location of buried pipe lines and other concealed magnetic metalwork is an obvious application to civil engineering practice.

***Electrical Methods.*** The electrical properties of earth materials, consolidated or unconsolidated, vary widely. Generally speaking, rocks, with the exception of the metallic ores, are electrically conductive in proportion to volume, size, continuity, and distribution of voids, and void fluids present. Various types of unconsolidated materials differ significantly in voids and contained fluids; and consolidated rocks, for example sandstone and granite, likewise differ in porosity and fluid content. These differences affect the conductivity or its reciprocal resistivity. The contrasts between consolidated and unconsolidated materials are usually of a higher order than differences within the two groups; hence, electrical exploration for depths of unconsolidated material is generally successful.

Whereas some rock masses, as sulfide ore bodies, give rise to spontaneous electric currents, most lectrical exploration for engineering ends is carried on by artificially energizing the ground.

*Equipotential Method.* If current is introduced into the ground by means of two electrodes, either point or line, current flows be-

tween them because of the difference in potential. Equipotential lines along which no current flows are traced by two nonpolarized "search" electrodes connected through an amplifier to headphones. One of these remains fixed, while the other is moved until minimum sound is received in the headphones, at which position the two "search" electrodes are on the same equipotential line. If the ground were homogeneous and isotropic, the equipotential lines would be symmetrically arranged about the power electrodes. The disposition of potential and current lines for homogeneous ground is shown in Fig. 12-9. If, however, masses of better or poorer conductivity are

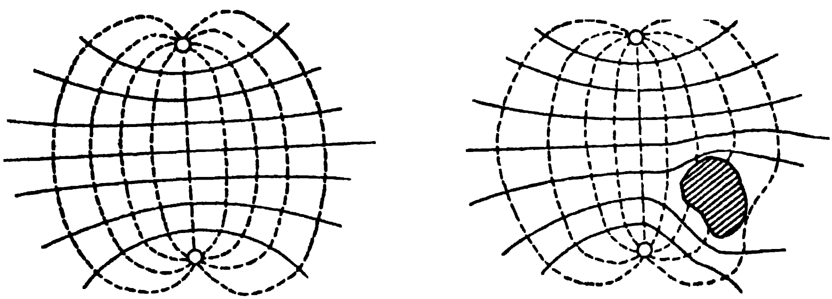

FIG. 12-9. *Left.* Disposition of current and potential lines for homogeneous ground. *Right:* Disposition of current and potential lines for non homogeneous ground. (From Eve and Keyes, courtesy of the U. S. Bureau of Mines)

embedded in the ground, distortions of the equipotential lines result. A mass of better conductivity "attracts" the current lines and "repulses" the equipotential curves. A mass of poorer conductivity causes opposite deflections. The effects are diagrammatically shown in Fig. 12-9. The long axis of an elliptical deformation is parallel to the strike of steeply dipping formations.

Determinations of the equipotential lines or potential profiles have been used in the location of ore bodies buried in glacial drift, delineation of structure beneath soil, and location of buried metallic objects. The method is best suited to the study of geologic formations with steep or vertical contacts.

*Resistivity Methods.* In engineering practice, resistivity measurements have been the most widely employed of the electrical subsurface exploration methods. Where the ground investigations deal

with horizontal or low-dipping bodies, resistivity measurements are effective. Figs. 12-10 and 12-11 show the results of resistivity measurements as affected by vertical changes of material. Measurements of the potential differences about one of the power electrodes or between two can be made, and by supplementing current measurments the resistivity can be calculated. Experience in Kansas shows that determinations of depth to bedrock are generally accurate to within 10 per cent.

A commonly used arrangement of electrodes is known as the Wenner-Gish Rooney method. Two reading, or potential, electrodes

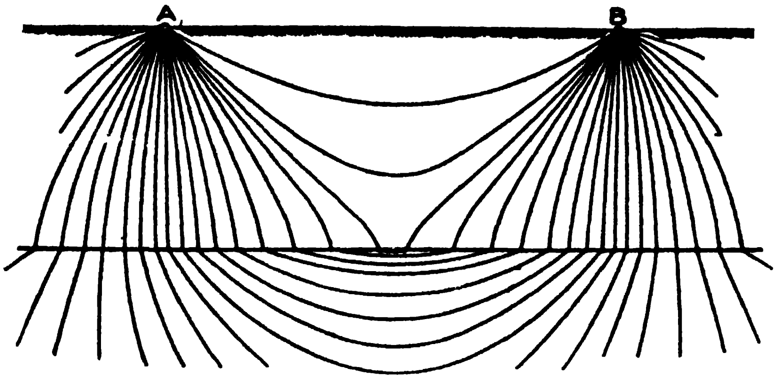


FIG 12 10 Lines of current flow in layered section (After S Weaver. Reproduced by publisher's permission from *Geophysical Exploration*, by C. A. Heiland, Prentice Hall, Inc)

are placed in line with two current electrodes, so that the distances between each are equal (Fig. 12-12). In this arrangement,

$$\rho = 2\pi a \frac{V}{I}$$

where $\rho$ = resistivity (in ohms per unit distance); $a$ is the distance in centimeters between electrodes; $V$ is the difference in potential between intermediate electrodes (in volts); and $I$ is the current in amperes flowing between end electrodes. Substituting $R$ for $\frac{V}{I}$, the expression is written $R = \frac{\rho}{2\pi a}$; hence the depth of exploration approximates the electrode separation. Other electrode arrangements are used, but the one just described is the most common.

As the spacing between the electrodes is increased, depth of exploration is greater. Experience has shown that materials at greater depths than the space between electrodes has little effect on the values of $\rho$—the specific resistivity of material, expressed in ohm-centimeters (the resistance in ohms between parallel faces of a centimeter cube of the material). The value obtained represents, for nonhomogeneous material, the average or apparent resistivity.


FIG 12 11. Results of resistivity of measurements as affected by vertical changes of materials Depth of penetration increases with the width of spacing between the electrodes. Generally the depth of bedrock beneath the ground surface is taken as that value of electrode spacing at which the curve takes an upward trend because of the high resistivity of rock as compared to earth or loose rock. (From Shepard, courtesy of the U. S. Bureau of Public Roads)

From the preceding discussion it can be seen that there are two possibilities of exploration. First, *horizontal* variations of material are detected by maintaining a constant spacing of the electrodes along an exploratory traverse. Thus if a 20-foot spacing of electrodes is maintained, with tests at every 20-foot station along the traverse, a depth of approximately 20 feet is explored. From the data, resistivity curves are drawn with resistivity values as ordinates and traverse distances as abscissae of the points. The curve for a step traverse over a deposit of sandy gravel is shown in Fig 12-16

Second, *depth data* are obtained by progressively changing the spacing of the electrodes so that deeper strata affect the values of $\rho$. In shallow exploration, for example, the initial electrode spacing might be 6 feet, with subsequent spacings of 9, 12, 15, etc., feet. The data are plotted as curves with resistivity values as ordinates, and electrode spacings as abscissae.

If other complications are absent, an abrupt change in the curvature of a resistivity profile indicates a change in nature of the under-

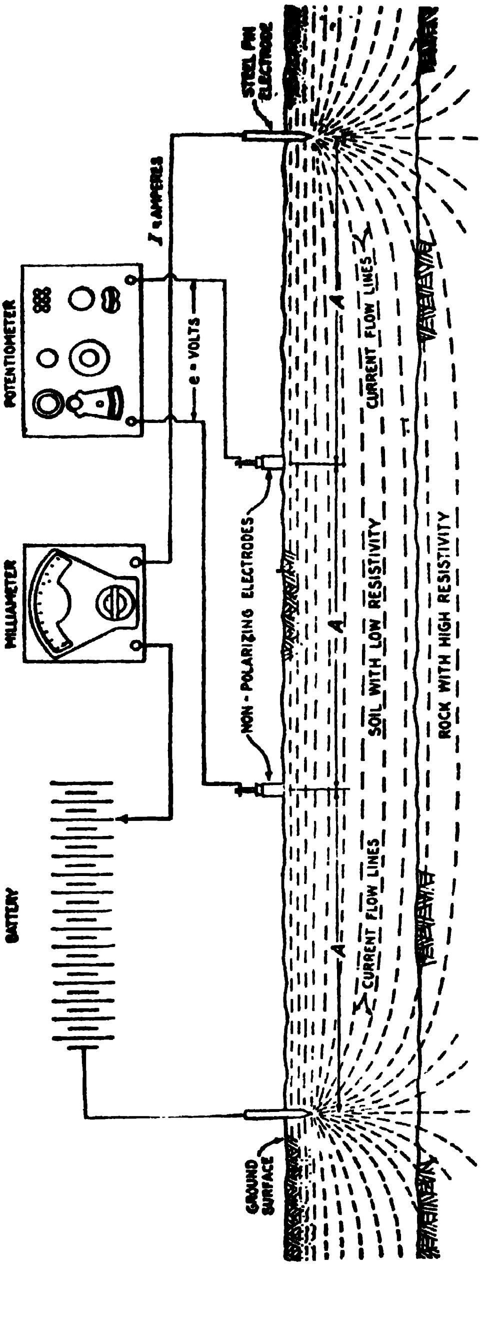


FIG. 12-12. Arrangement of apparatus for measuring electrical resistivity. (From E. S. Shepard, courtesy U. S. Bureau of Public Roads)

lying materials at a depth approximately corresponding to the spacing of the electrodes for the point of curvature change. A rising curve indicates increasing resistivity with depth, as might be occasioned by rock or gravel. A flat or descending curve indicates decreasing resistivity such as might be caused by clays or other soil types. More precise methods of handling the data, involving computation and graphical solutions, make quantitative interpretations possible. By quantitative analysis of the apparent resistivities, the

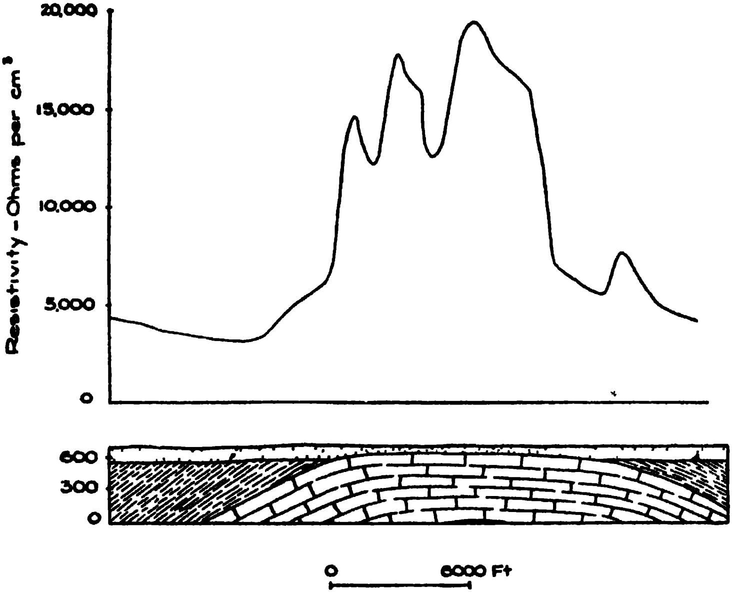


FIG. 12-13. Fold determined by resistivity measurements. (From Hubbert, courtesy of the A.I.M.E.)

true resistivity of a member of a two- or three-strata series can be determined, with obvious advantages in forecasting subsurface lithology and structure.

Other electrical methods have been developed. To date, however, the resistivity methods have proved most useful in engineering practice.

*Engineering Applications.* Petroleum engineers have used resistivity methods widely and successfully in subsurface structure

mapping. Buried anticlines, the most common type of structure favorable to oil accumulation, can be traced by determining depths to strata of greater or lesser resistivity. An example of structural determination by the method is illustrated in Fig. 12-13. In this instance a fold concealed by glacial till brings a limestone of high resistivity near the surface. Another example of engineering application, the determination of rock excavation in a highway cut through a till-mantled hill, is shown by Fig 12-14.

Mining engineers have applied resistivity methods to subsurface

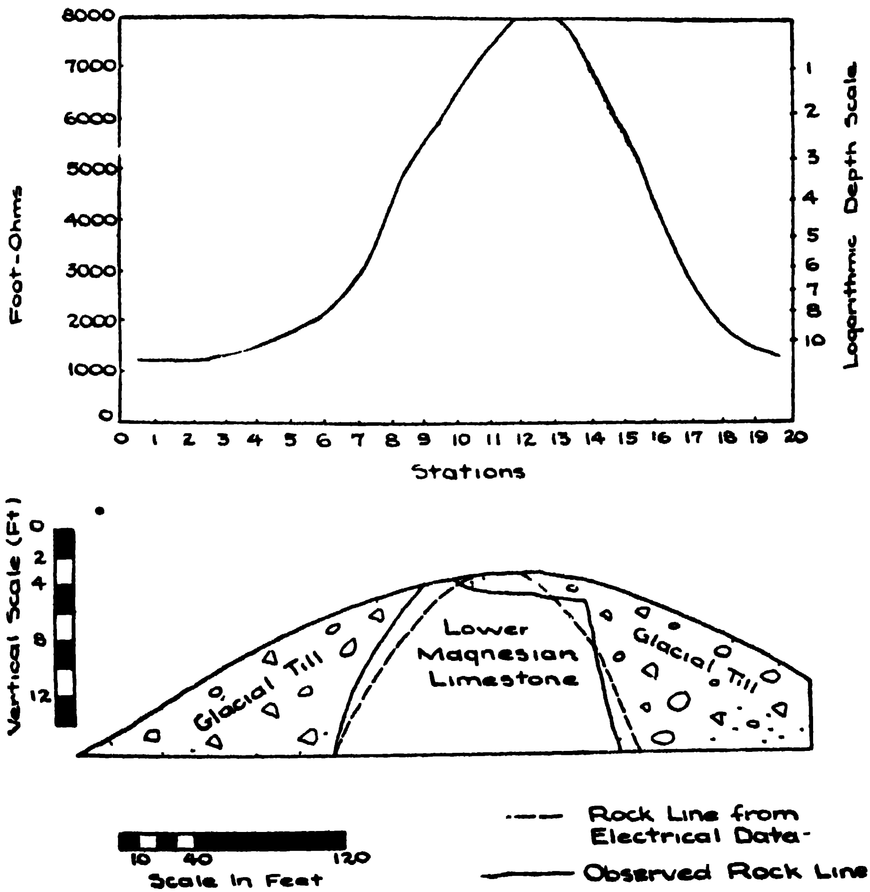


FIG. 12 14 Determination of rock excavation in a projected highway cut through a till mantle hill. (After Kurtenacker, courtesy of the A I M E)

structure determination and to the delimitation of certain economic deposits.

Civil engineers have found increasing use for resistivity methods. Examples of civil engineering problems to which resistivity methods have been successfully used are determinations of depth of bedrock; determinations of subsurface structures that may affect engineering design or construction; classification of subsurface material, as earth, loose or broken rock, and consolidated rock (necessary in letting contracts); location and delimitation of construction materials; and location of water-bearing strata.

*Determination of depth to bedrock.* Many types of construction require a determination of the depth of overburden.

On the Connecticut River in New Hampshire, for example, the part of the valley across which a dam was to be built is a buried pre-glacial gorge, choked with a glacial fill consisting of till, gravel, sand, and clay. The underlying bedrock is schist and phyllite. It was required to determine the depth to bedrock at enough points to outline the conditions in the vicinity of the dam. The depth of overburden varies along the axis of the dam from 0 to nearly 150

TABLE 12.1.[3] RESULTS OF ELECTRICAL DETERMINATIONS DIRECTLY CHECKED BY THE DRILL

| Hole Number | True Depth to Rock (feet) | Predicted Depth (feet) | Predicted Depth in Relation to the True Depth (%) |
|---|---|---|---|
| 1 | 29 | 24 | 83 |
| 7 | 27 | 41 | 151 |
| 9 | 108 | 108 | 100 |
| 10 | 100 | 118 | 118 |
| 11 | 56 | 53 | 95 |
| 12 | 50 | 43 | 86 |
| 13 | 101 | 105 | 104 |
| 14 | 142 | 148 | 104 |
| 20 | 167 | 115 | 69 |
| 21 | 147 | 142 | 97 |

[3] From Crosby, I. B.

feet. Table 12.1 shows the results of the electrical determinations as compared with check drilling.

For five of the ten holes, it will be noted, the electrical predictions were checked within 5 per cent by the drill. Three of the predictions checked within 20 per cent, and two holes, Nos. 20 and 7, were in marked error. In hole No. 20 a "hill" of gravel of high resistivity was mistaken for bedrock. Hole No. 7 was located near the edge of the buried gorge. It is thought the drill struck a high point of rock whereas the electrical determination was influenced by surrounding material.

The rapidity, economy, and relative accuracy of the electrical subsurface methods of bedrock depth determinations recommend them. They supplement but do not supplant drilling and geological investigation.

*Subsurface structure determination.* Fault zones because of crushing and water content may be determined in the course of subsurface studies.

Reduced resistivities discovered in the investigation of an aqueduct site revealed a crushed and water saturated fault zone 350 feet wide in the granite. The site was rejected. Many other examples could be cited from explorations of dam foundations. The significance of this type of structural determination is apparent.

*Location and delimitation of construction material.* Resistivity exploration of gravel and sand deposits can be advantageously carried on in some instances. An illustration is found in Fig. 12-15. A preliminary traverse with tests at 20-foot intervals was run along the old logging road where gravel was suspected. Tests showed an increasing amount of sand and gravel as a peak was reached between stations 1 + 60 and 5 + 00. Graphs A and B and C (Fig. 12-16) show the resistivity curves and logs of bore holes at these locations. Subsequent traverses, as indicated by the map, outlined the gravel-sand deposit. The area within the 5000 ohm-meter contour was found to contain a gravel stratum 8-10 feet thick within 12 feet of the surface over much of the area. From the data of this survey, the area of Fig. 12-15 designated as *A* is estimated to contain some

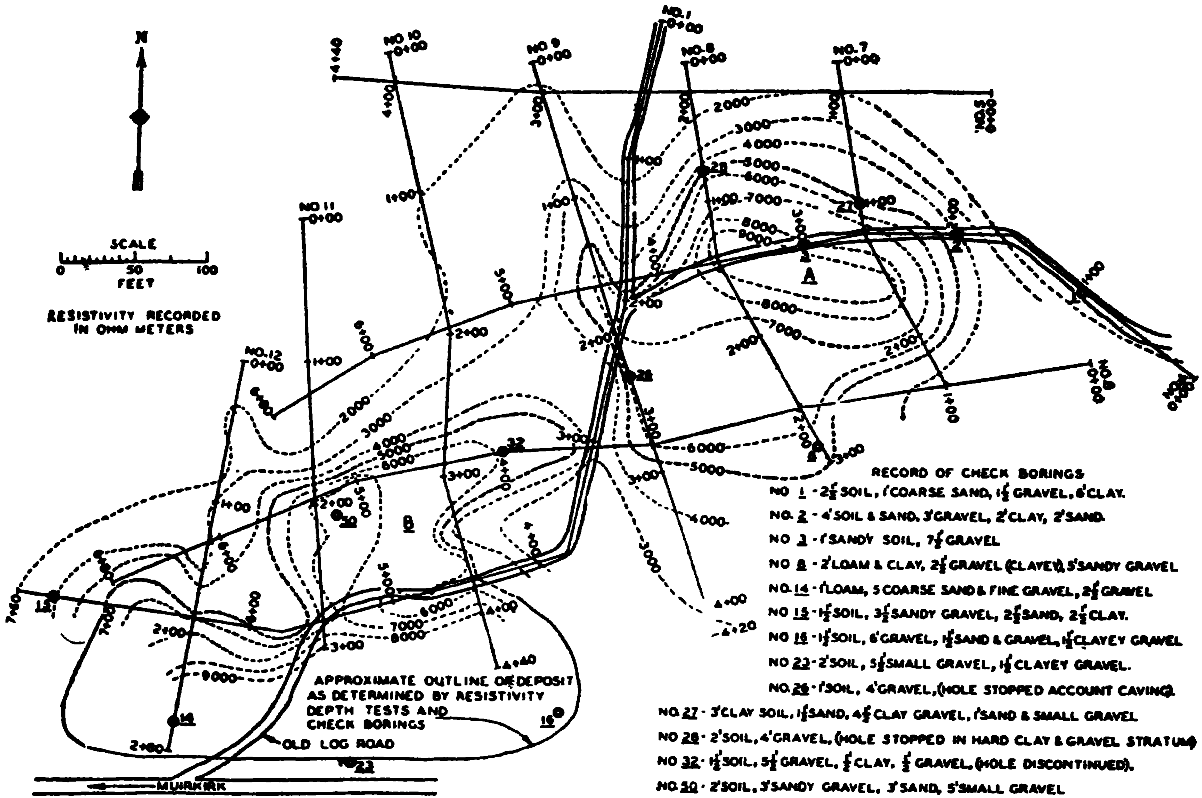


FIG. 12 15. Resistivity contour map of a deposit of sandy gravel. (From W. Moore, courtesy *Pit and Quarry Magazine*)

10,000 cubic yards of sandy gravel with some clay and sand spots, within 15 feet of the surface. The area designated as *B* is estimated to contain 15,000 cubic yards of gravel.

Moore[4] estimates that a resistivity crew of four, an operator, recorder and two laborers can run about 2000 to 4000 feet of traverse a day and may be expected to make twenty to thirty depth tests involving about 30 feet as compared with four or five 6-inch augur holes to a depth of 12 or 15 feet per day expected from two men.

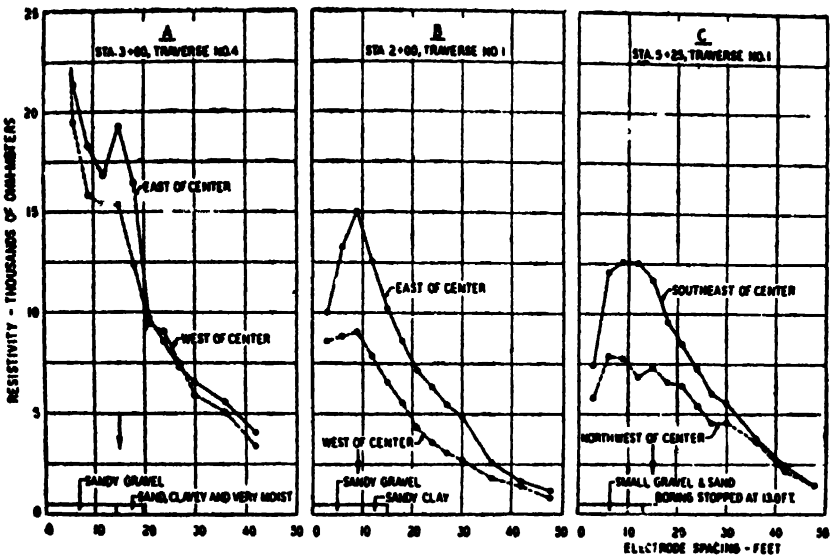


FIG. 12 16 Resistivity depth tests in a sandy gravel formation underlain by clay or clayey sand. (From W Moore, courtesy of *Pit and Quarry Magazine*)

The method is not without failures, however, and in common with all geophysical exploration, the data must be correlated with surface geology and checked by borings to be effective and economical.

*Subsurface water studies.* The location of subsurface water supplies has been attempted, and locally results of value have been obtained. The Illinois Geological Survey is successfully using elec-

[4] Moore, W., "Prospecting for Gravel Deposits by Resistivity Methods Described," *Pit and Quarry*, Vol. 38, 1945, p 79

trical prospecting for gravel-sand aquifiers in glacial drift. Both potential and resistivity methods have shown promise, but the limitations and difficulties do not ordinarily make these methods attractive. In regions of gentle dips, the presence and structure of an aquifer—for example, a porous sandstone stratum—may be determined. In areas of strongly deformed sediments or of crystalline rocks, however, geophysical location of water supplies has yet to be perfected.

*Seismic Methods.* The elastic properties of earth materials vary widely. Seismic methods of geophysical exploration are based on the variation of elastic properties. Differences in the elastic coefficients of different layers give rise to reflections and refractions of seismic waves, which are treated in the same manner as are the comparable phenomena of geometrical optics. The instruments are designed to measure and record the speed of propagation of such waves in earth materials. The velocity measurements make possible inferences as to the attitude, nature, distribution, and structure of subsurface materials.

The speed of the seismic waves in rock is influenced in large measure by the degree of consolidation.

TABLE 12.2.* REPRESENTATIVE LONGITUDINAL WAVE VELOCITIES

| *Material* | *Ft/Sec* |
|---|---|
| Alluvium (surface deposits) | 1805- 4921 |
| Glacial drift (type not specified) | 1588- 5578 |
| Sands, sandy clays, and clay | 1540- 6234 |
| Sandstone, shale | 3055-13,780 |
| Limestone | 3200-20,998 |
| Granite | 13,124-18,603 |
| Gneisses and schist | 10,170-24,406 |
| Slate | 10,500-16,405 |

* Data from Heiland's *Geophysical Exploration.*

The data of Table 12.2 are representative, although based on relatively few determinations. The data at least bring out a contrast between crystalline and thoroughly indurated rocks, on the one hand, and the more loosely coherent and unconsolidated material on the other. In general, velocity ranges of 1000-6000 feet

per second indicate unconsolidated or weakly consolidated material. It will be seen that the contrasts are not sufficient to distinguish clearly between sand and clay or between other types of unconsolidated materials.

Two methods are of common use in seismic exploration. These are known as reflection shooting and refraction shooting. Reflection shooting is generally used for deep exploration, commonly greater than 2000 feet. Refraction methods are better adapted to lesser depth and, since most engineering explorations are of the shallower types, only the refraction method is described here.

*Refraction Methods.* In refraction determinations, a blasting cap or small charge of dynamite is exploded at or near the surface at a point known as the shot-point. From the shot-point, elastic waves travel outward in all directions. In profiling, detectors (seismometers) are spaced at intervals in line with the shot-point (Fig. 12-17). The disturbances, commonly amplified, are recorded photographically on moving film. Time intervals are recorded on the film strip by time lines which are obtained from a tuning-fork device, electrically driven. The tines have peep slits which coincide when the tines are in the neutral position; hence two lines are photographically recorded on the films for each complete cycle. The instant of detonation is electrically transmitted from the shot-point to receivers and is indicated on the film strip. In one method a wire on the blasting cap is hooked up with the galvanometers of the receptors in such a way that when it is broken by the detonation a kick is given to the galvanometers, and the time of explosion is simultaneously recorded on the curves for each receptor.

A typical photographic time record is shown in Fig. 12-18. In this figure the three curves represent the record of three detectors spaced out in line with the shot-point. It is assumed that seismic energy follows that path which enables the impulse to reach the receptor in the shortest time. In Fig. 12-17 it will be observed that at $D_1$, close to the shot-point, the first disturbance, has traveled directly through the soil, with speed which is expressed as $Ve = \frac{L_1}{T_1}$. At

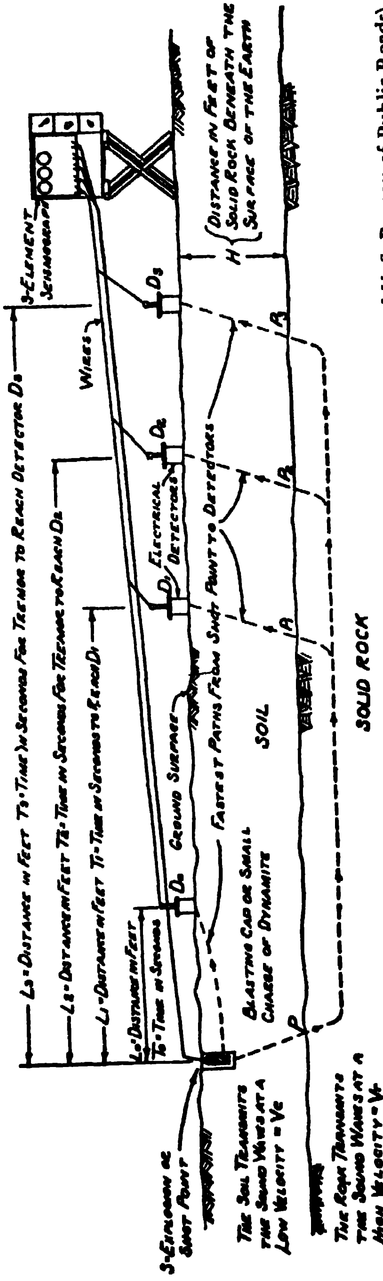


FIG. 12 17. Sketch showing fundamental principles of seismic exploration (From Shepard, courtesy of U S. Bureau of Public Roads)

greater distances from the shot-point, waves from the explosion that have followed the paths $SPP_2D_2$ and $SPP_3D_3$ are the first arrivals at $D_2$ and $D_3$. Because $SPP_2$ is common to both circuits the velocity in rock, $Vr$, can be expressed as

$$Vr = \frac{L_3 - L_2}{T_3 - T_2}$$

Without introducing serious error, it may be assumed that the angle of refraction at point $P$ is 90°, and that $PP_3$ is equal to $L_3$. If the

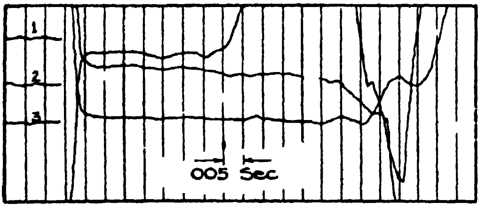


FIG. 12.18 Time record of a seismic exploration. Calculation of depth to bedrock: shooting distances, $L_1 = 50$ ft, $L_2 = 100$ feet, $L_3 = 150$ ft. Time of wave travel from shot to detectors $T_1 = .0355$ sec, $T_2 = .071$ sec, $T_3 = .074$ sec.

$V_e$ = velocity of wave in earth =

$$\frac{L_1}{T_1} = \frac{50}{.0355} = 1400 \text{ ft/sec}$$

$V_r$ = velocity of wave in rock =

$$\frac{L_3 - L_2}{T_3 - T_2} = \frac{50}{.003} = 16{,}700 \text{ ft/sec}$$

$$H = \text{depth to rock} = \frac{V_e T}{2} - \frac{L V_e}{2V_r} =$$

$$\frac{1400 \times .074}{2} - \frac{150}{2} \times \frac{1400}{16{,}700} = 15.5 \text{ ft}$$

(From F. R. Shepard, courtesy of the U. S. Bureau of Public Roads)

direct wave through the earth and the refracted wave arrive at the same time at a detector, the distance from that detector to the shot-point is called the critical distance. In making determinations to bedrock, $L$ should approximate the critical distance for best results. Values of $Ve$ (earth velocity) and $Vr$ (rock velocity) are usually such that the critical distance $L$ approximates 2.2 $H$ (depth of soil).

It will be noted that in depth determinations of this type, the

average depth between shot-point and detector is determined. A reverse profile, from which the slope of the bedrock surface can be estimated, is established by shooting at the other end of the line. In northern Wisconsin-Michigan fifty of sixty depth-to-bedrock determinations using this method in a survey for a canal route were found to be accurate within a foot.

Time-travel curves drawn from the data obtained by seismic methods assist in interpretation. The ordinates are distances from the shot point; the abscissae are time intervals. In practice the velocities in the different layers are determined from the time-travel curves. The method of bedrock depth determination is illustrated by the results of the U. S. Bureau of Public Roads experiments at the Arlington Memorial Bridge. Fig. 12-18 reproduces the time record and calculations for one station.

The determination of the presence and configuration of more than one refracting layer in depth complicates analysis, but problems involving strata of different elastic properties can be solved.

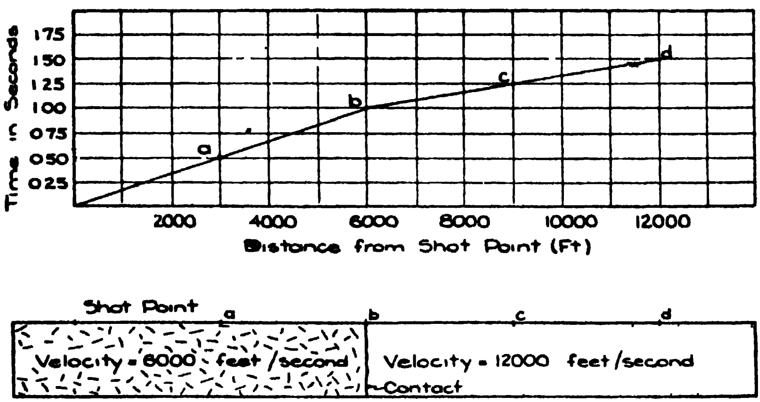


FIG 12-19. Time travel curves for conditions in the cross section (From M. P. Billings, *Structural Geology*, courtesy Prentice Hall, Inc New York)

If vertical or nearly vertical boundaries of rock masses of different elastic properties are present, the location of the boundaries can be established as illustrated in Fig. 12-19. Because a similar curve might be the result of horizontal differences, another shot at a distance

from the first is fired. If the boundary is vertical, the break in the curve remains at the same place wherever the shot may be placed.

Of the geophysical methods, those most used in civil engineering explorations are seismic and resistivity determinations of depth to bedrock and exploration of material sources. A brief comparison of boring methods and seismic and resistivity determinations is shown in Table 12.3.

TABLE 12.3.* RELATIVE MERITS OF GEOPHYSICAL AND COMPARABLE BORING METHODS

| Method | Equipment Cost, $ | Weight, lb. | Minimum Crew | Cost, $/Ft | Advantage | Disadvantages and Limitations |
|---|---|---|---|---|---|---|
| Hand auger | 10 | 10 | 1 | .50-1 | Soil samples | Limited by gravel and ground water 30 ft. maximum depth. |
| Jeep mounted power auger | 3500 | 3000 | 1 | 30-1 | Soil samples | Limited by boulders and ground water. |
| Wash boring | 500 | 200 | 2 | 30-1 | "Washed" samples | Cannot bore gravel or boulders. |
| Seismic | 1000 | 150 | 3-4 | .25-.50 | Not hampered by boulders | Estimate only for character of soil. Unreliable if soil depth (rock surface) is irregular. |
| Resistivity | 500 | 25 | 2-3 | .25-.30 | Not hampered by boulders | Only estimates soil character. |

* After G. F. Sowers, *Trans. Am. Soc. Civil Engrs.*, Vol. 118, 1952, p. 959.

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# CHAPTER XIII

# EARTH HISTORY

On many of the geological maps which an engineer may consult, it will be found that rocks are shown as *Cambrian, Ordovician, Silurian,* or by other specific time designation. In most geologic reports, historical terms are used, without explanation. In the engineering literature also, many references could be cited wherein the nomenclature of historical geology has been used. The engineer will find it of value, therefore, to be acquainted at least with the geological timetable and to appreciate the basis for the major units of the time division, and also to be familiar with some of the basic principles underlying historical geology.

Earth history necessarily involves dates and events. Archeological restorations of human history are based in large measure on remains; similarly, geological history is recorded by remains, both organic and inorganic. The kinds of rocks and their minor structures throw light on the events and conditions which produced them. Unconformities and fossils are of especial significance. And if geologic history is to be of wide significance, the interrelations of many regions must be established; stated otherwise, geological correlations must be worked out. The major divisions of geologic time, established by broad regional correlations, constitute the geologic timetable.

## Geologic Time

The length of geologic time is probably the most difficult concept of historical geology to grasp. The age of the earth has been variously estimated by several different methods. Archbishop Ussher,

of Dublin, in the 17th-century, through calculations based on Biblical data, placed the date of creation at 9 o'clock on the morning of October 26, 4004 B.C. The rate of growth of the Nile delta had suggested to Herodotus nearly two thousand years before Ussher's time that many thousand years were recorded in its building. Annual layering of certain lake-deposited shales of Colorado and Wyoming indicate that six and a half million years were required to produce the 2600 feet of that particular sedimentary formation alone. As we have seen in the discussion of rock weathering, sodium is leached from the rocks and carried into the sea where it is concentrated by evaporation. Therefore, calculations of the amount of sodium in the sea and a knowledge of the annual increment gives us a formula whereby the age of the ocean might be approximated:

$$\frac{\text{Sodium in the sea}}{\text{Annual increment of sodium}} = \text{age of the sea}$$

This works out to be about 100 million years. The rate of annual increment, however, has not been constant and the figure is of only passing interest. More recent researches have demonstrated a new and apparently reliable method for the determination of the age of rocks. Minor amounts of uranium and thorium, the two chief radioactive elements, occur in all rocks. These elements spontaneously undergo slow disintegration into helium and lead with the evolution of heat. The physicist has been able to determine the rate of this atomic disintegration, and no known conditions of heat, pressure, or associations affect the rate of transformation. The ratio of radioactively produced lead to uranium in a crystal of one of the uranium minerals makes it possible to determine its age. Incidentally, radioactively produced lead has a slightly different atomic weight from ordinary lead. The age of the oldest rocks that have been determined by radioactivity is computed at approximately 2.5 billion years. Since these rocks were intrusives in still older rocks, it follows that an approximation of three billion years is probably within the right order of magnitude for the age of the oldest rocks now exposed at the surface.

### The Geologic Timetable

The span of earth history, which has been indicated as some three billion years, is by no means completely represented by the rocks now exposed. Everywhere breaks of various magnitude occur which subdivide geologic history into units analogous to the subdivisions of human history. The major units of geologic time are called *eras*, and the lesser units of time which make up the eras are called *periods*. The commonly accepted timetable which is applicable to the rocks that occur in all parts of the world is shown in Table 13.1.

The major divisions of the time scale—eras—are separated from each other by major breaks in the geological record. The major breaks are the results of widespread uplifts and consequent erosion. Over widespread areas of the earth's surface uplifts which brought sedimentary beds into the erosional zone were accompanied by intense folding and at many places by igneous activity. These widespread and long enduring changes in physical environment caused marked evolutionary changes in the plants and animals of the time, so that when seas readvanced over the eroded area, new assemblages of plants and animals had come into existence. Almost universally, great changes are found in the assemblages of organic remains entombed in the rocks of different eras.

Similar breaks in the geologic record, but of lesser significance than those delimiting the eras, mark off divisions within the eras called *periods*. Breaks of still less significance subdivide the periods. A *formation* is a group of rocks composed of similar materials and displaying common group characteristics, with boundaries that can readily be traced in the field. A formation, then, is a mappable, natural unit of sedimentary strata, surface volcanics, or their metamorphosed equivalents. Formations are named commonly from a locality at which they are typically developed and well exposed. Formations are the lithologic units that are shown on most geological maps.

TABLE 13.1. DIVISIONS OF GEOLOGICAL TIME

| | Era | Period | | Approximate Age in Years |
|---|---|---|---|---|
| | Cenozoic Era (or period) | Quaternary | Recent; Pleistocene or Glacial | |
| | | Tertiary | | 60 million |
| | Mesozoic Era | Cretaceous | | |
| | | Jurassic | | |
| | | Triassic | | 200 million |
| | Paleozoic Era | Permian | | |
| | | Pennsylvanian | Carboniferous | |
| | | Mississippian | Carboniferous | |
| | | Devonian | | |
| | | Silurian | | 350 million |
| | | Ordovician | | |
| | | Cambrian | | 520 million |
| The Precambrian | Proterozoic Era | Keweenawan | | |
| | | Huronian (Animikie) | | |
| | Archeozoic | Timiskaming | | |
| | | Keewatin | | 3 billion |

## HISTORICAL INTERPRETATIONS

The reconstruction of past geologic events is aided by recognition of rock types, structures, and unconformities, and especially by recognition of any organic remains preserved in rocks.

***Lithology.*** The mineralogical and mechanical compositions of sedimentary rocks carry implications as to climate and topography. For example, an arkose resulting from the disintegration of a granite implies severity of climate—either cool or arid. Bauxite deposits that result from chemical weathering of a syenite imply warm moist lowlands. Angularity of clastic fragments means in general short transportation. Volcanic ash and tuff beds, lava flows and intrusions, indicate past igneous activity in many regions which at the present time are entirely free from any volcanism.

***Minor Features.*** The minor structural features of many sediments give some clue to the environment in which they were deposited. Ripple mark and cross-bedding are relatively shallow water features which are not commonly formed in depths of water greater than two or three hundred feet. Mud cracks, while they may be formed beneath the water, usually indicated exposed mud flats. Occasionally even rain prints and frost marks have been preserved Buried soil horizons or weathered zones often indicate something as to the conditions prevailing at the time and place of weathering.

***Unconformity.*** Unconformities already have been described and figured (page 191). Because of their significance in the interpretation of the geologic record, an example is introduced here from the Grand Canyon region. Fig. 13-1 represents the cross section exposed along the canyon wall in the Shinumo Quadrangle, Arizona At the bottom of the section is granite. That this is not the oldest rock in the region, however, is shown by inclusions of the overlying schist in the granite and by the penetration of the granite into the schist. The schists, which are in large part of sedimentary origin as shown by bedding, were deposited in some water body, consolidated, folded, metamorphosed, and then intruded by the granite. Erosion followed the intrusion. On top of the eroded Vishnu schists, sediments were deposited in the water that subsequently flooded the erosion surface. The line of contact between these two sequences of rock marks the unconformity in this area between the Archeozoic

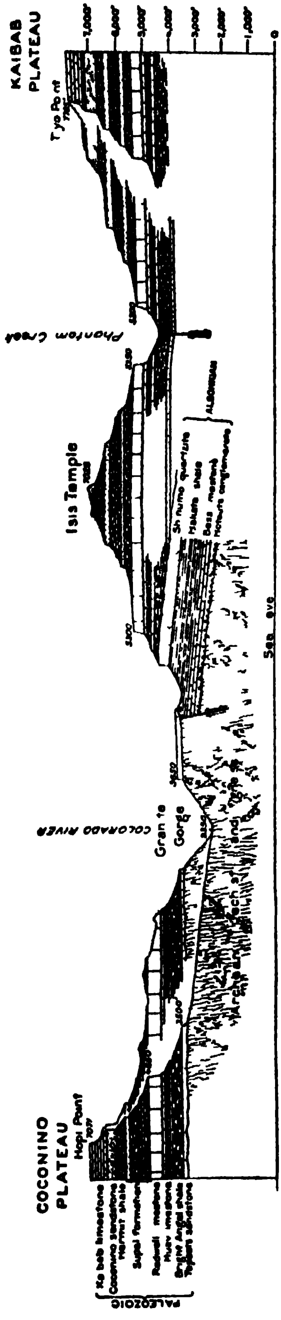



Fig. 131 Cross section of Grand Canyon from Hopi Point on the south rim to Tiyo Point on the north rim

and Proterozoic. Following the deposition of Proterozoic rocks, the land was again warped up and subjected to erosion. The next deposits above were deposited in the upper Cambrian seas which advanced over the region. Uplift of the land or recession of the sea level again brought the area above water for the succeeding sediments above are Carboniferous in age. The line separating the rocks of the Cambrian section from those of the Carboniferous is an unconformity; strata of Ordovician, Silurian, and Devonian ages are missing. Either the missing beds were never deposited or were eroded before the advance of the Carboniferous sea. Recession of the sea and erosion followed the deposition of the Red Wall limestone (Mississippian) and a readvance of the sea in Permian time gave opportunity for deposition of the Hermit shale, Coconino sandstone, and Kaibab limestone. Thus it may be seen that in the section diagramed in Fig. 13-1, a record of diastrophism and erosion as well as deposition and igneous activity is presented

Natural exposures showing any such complete record are rare indeed. Rather, information must be pieced together from scattered exposures. Thus, it may be found that the granites of one locality penetrate a certain quartzite. At another place it may be found that the same quartzite is unconformably overlain by a conglomerate. Elsewhere the conglomerate may be seen to be overlain conformably by sandstones, shales, and limestones. By assembling the data from the various exposures in a region the geologic relations and a sequence of events may be worked out. The significance and importance of unconformity in the interpretation of geologic history are thus apparent. Unconformity may not be readily distinguishable in the field, particularly in areas where the rocks above and below the unconformity are highly deformed. Disconformities are breaks in the depositional sequence above and below which the rock strata are essentially parallel. The detection of disconformity may depend on paleontological evidence or on the recognition of the absence of certain strata normally present. Occasionally the presence of unconformity may not be recognized until field mapping brings out the

fact that one formation immediately overlies different formations at different places.

***Fossils.*** Fossils are any trace of plants or animals found in sedimentary deposits older than post-glacial. The two most important conditions favoring the preservation of plant or animal fossils are possession of hard parts and rapid burial. Even such soft-bodied animals as jellyfish have been preserved as fossils, but they are exceptional. Organic remains are preserved in various ways. These are: (1) *Actual preservation* of the organism intact, for example the mammoth elephants found frozen in stream gravels in Siberia. Actual preservation is, of course, extremely rare. (2) *Molds.* After burial the plant or animal itself may disappear due to solution and decay, but the imprint in soft sediments may be preserved. (3) *Casts.* Molds may be filled with some other substance making natural casts similar to castings which are made from molds in a foundry. (4) *Replacement.* Mineral material, for instance silica, or other mineral matter may replace the organic remains bit by bit, faithfully preserving the structure. Perhaps the best known example of this type of preservation is petrified wood. (5) *Permineralization.* Mineral matter, silica or other substances, often infiltrates into the interstices and small voids, where its deposition "petrifies" the remains. (6) *Carbonation.* Plants, by slow decay, often leave carbon films which beautifully preserve the detail of the original material. (7) *Traces.* Animals that walked or crawled across soft sediments left tracks and trails a few of which have been preserved; excreta of various animals also have been occasionally preserved, and such curiosities as gizzard stones have been identified.

Within the last hundred and fifty years, the true nature of fossils as a record of past life has been accepted by nearly all. A tremendous volume of research on fossils has been accomplished, and at present fossils are useful to the geologist in a number of different ways. By the study of fossils the orderly course of evolution has been demonstrated. Although the Cambrian period is the first in which fossils became at all abundant, and the Precambrian rocks are virtually barren of fossils, nevertheless, the stage of evolution at the beginning

of the Paleozoic indicates that life had originated far back in Precambrian time. For each period of geologic time since the beginning of the Paleozoic era, a characteristic assemblage of fossils has been recognized. Certain life forms had a widespread geographical distribution and only a limited span of existence; some species existed only a fraction of a geologic period. These fossils of short time range, if widespread and abundant, are especially useful as horizon markers. By their recognition it is possible to establish the essential time equivalence of the layers in which they are found, although the exposures may be far apart. It should be emphasized that the sequence of fossil forms has been established by field and laboratory work and does not depend on any theory. No species once extinct has ever reappeared.

The study of types and distributions of marine fossils has given information on the extent of seas of the different periods. In a similar way land fossils indicate not only land areas but also connections between them which afforded migration routes. Paleontology thus has helped the geologist in the construction of *paleogeographic maps* which outline in a general way the land and sea areas of a particular time. Fig. 13-2 illustrates a paleogeographic map for the middle Silurian.

Much information is given by fossils as to the climate of the times in which they lived. The distribution of Arctic types in Pleistocene sediments far to the south of their normal habitat today indicates recent climatic changes of far reaching effect. By analogy the habitats of certain fossil organisms are assumed to have been similar to those of present representatives. Thus, where colonial corals of Silurian age are found in Wisconsin and farther north, in association with other forms also presumed to have been warm water types, it may be assumed that the shallow sea which covered the area was relatively warm.

### Correlation

If there were no soil mantle or complications of structure, metamorphism and intrusion, the correlation, or matching, of the beds exposed at one place with the same or equivalent beds at other

localities would be a relatively simple matter. Because of the fragmentary character of the record, however, it is often difficult to match, or correlate, rock formations from exposure to exposure, locality to locality, or from drill hole to drill hole. There are several

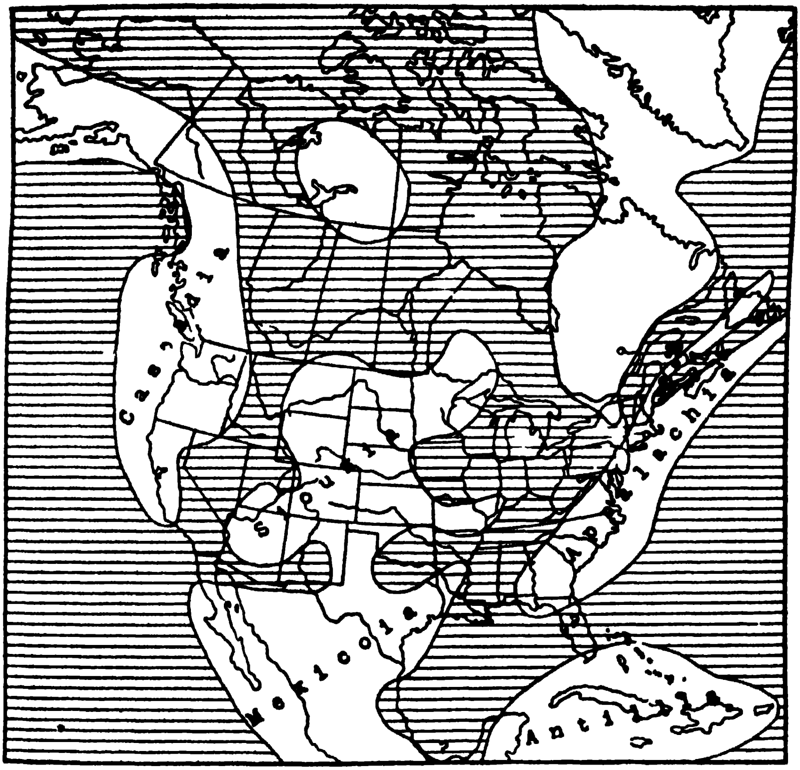



FIG. 13.2. Generalized paleogeographic map showing sea and land areas in North America during Middle Silurian time. This was the greatest Silurian sea. White areas land, ruled areas sea. Small circles show volcanoes in Maine, New Brunswick, and Nova Scotia. Principal data (modified) from maps by C. Schuchert and R. Chamberlain.

ways in which correlation may be established. (1) It is often possible to establish the physical continuity of beds over short distances, (2) the discovery of guide fossils is the most certain means of identifying the stratigraphic position of a bed and establishing its correlatives; (3) within limited areas, lithologic similarity of beds is often used successfully; (4) like sequences of beds suggest possible correla-

tions, and the more beds involved in the sequences the less chance for error; (5) similarity of insoluble residues of carbonate rocks or of the minor mineral constituents of the insoluble rocks has been useful in establishing correlations.

Other means of correlating rocks are comparisons of the degree of metamorphism, amount of deformation, and number and variety of igneous intrusions present. These are somewhat less satisfactory and less conclusive than the preceding methods. Radioactive age determinations establish general time equivalence but do not establish precise stratigraphic correlation.

The correlation of rocks from place to place often has economic or practical significance. This is particularly true in drilling for water or petroleum. Certain beds may be known water-bearers or petroleum yielders. If the stratigraphic succession has been established in a region and the beds being drilled can be correlated with the equivalent beds in the established succession, the driller knows where he is stratigraphically and can estimate the depth to which he must continue drilling. It is recognized, of course, that thicknesses are variable and erosion may have eliminated some members of the succession. In a similar way the establishment of stratigraphic position of beds is of assistance in forecasting tunneling and mining operations.

It will be noted that the above discussion of the historical significance of fossils and rock characteristics draws largely on analogy with present-day conditions. This can be summed up tersely in the statement that *the present is the key to the past,* as first realized by James Hutton 150 years ago. This is another way of saying that the same processes at work today have acted in a similar way in the past, although it is recognized that the rate of action has varied from time to time. This doctrine of Hutton's is known as the principle of uniformitarianism.

### Resume of Geologic History

The farther back we go in geological history, the less certain is the interpretation of events. The oldest rocks so far recognized are

sedimentary rocks, intensely deformed and metamorphosed. The fact that they are of sedimentary origin means that they were derived from pre-existing rocks which were weathered in the same way that rocks are being weathered today. Nowhere in the world have any vestiges of a beginning been recognized. Consequently, there is as yet scant geologic basis upon which to found a hypothesis of earth origin. We do know, however, that there are no elements recognized in the earth that do not occur in the sun.

***Earth Origin.*** It is supposed by many that the sun is the parent of its attendant planets and their satellites. Various suggestions for the mechanism of origin have been proposed. Two American scientists, Chamberlain and Moulton, suggested that an errant star made a close approach to the sun. According to their view, the tidal forces generated by this celestial accident, aided by the sun's tendency to explosive eruption, partially disrupted the sun; the ejected sun material hardened into small solid particles, called *planetesimals;* the aggregation of planetesimals has brought the earth to its present size. Modifications of the original Chamberlain and Moulton hypothesis have been proposed by the British scientists, Jeans and Jeffrey, who propounded what is called the *tidal-gaseous hypothesis.* According to this hypothesis, a star made a sufficiently close approach to the sun to cause the ejection of a cigar-shaped filament or stream of gases which subsequently condensed into the several members of the planetary system. By either hypothesis, after the passing of the errant star, the gravitative pull of the sun has kept the ejected material, planetary bodies, under solar control. The tidal-gaseous hypothesis assumes that the earth went through a molten stage.

In recent years objections to these hypotheses have led to a series of new proposals. One of the currently favored ideas begins with an extremely diffuse dust cloud. The minute but real pressure of light from surrounding stars acting on the individual tiny particles of "cosmic dust" forces these towards a common center. With increasing density of the dust cloud, gravitational forces eventually become effective, with "collapse" of the volumes of maximum density

into a central body, the sun, and into minor centers, the planets and their satellites; in the process high temperatures were generated. The dust-cloud hypothesis and its variations are too recent to have been critically tested.

The surficial rocks of the earth's crust have a specific gravity approximating 2.75. The specific gravity of the earth as a whole is about 5.5, and that of the material at the center of the earth is perhaps 11. Unless an initially liquid condition is assumed, it is difficult to account for the density distribution. As the earth cooled and condensed, violent volcanism must have prevailed which brought waters and gases to the surface. Since the advent of surficial waters and the acquisition of an atmosphere, weathering and erosion have been at work. The geological record does not start, however, until after these processes had been operative for a considerable length of time, for, as has already been stated, the oldest rocks known show that they were by no means part of any original crust.

***The Precambrian.*** Radioactive determinations of age show that the earliest rocks with abundant fossils date back at least 500 million years. Similar age determinations reveal an age of some 2.5 billion years for the oldest rocks yet identified. Because all of the time before the beginning of the Paleozoic Era is included in the *Precambrian,* the latter therefore includes about 80 per cent of known time. How much older the earth is than the oldest rocks studied is a matter of pure conjecture. For several reasons the Precambrian history of the earth has not been worked out in the same detail as that of the following eras. In the older Precambrian, the rocks are highly deformed, intimately intruded by igneous rocks, and almost barren of fossils. In the later Precambrian, more detail has been achieved in working out the record.

Precambrian rocks are of the same types as those of more recent dates, showing that the same processes active today were acting then in the same way with similar results. Volcanic activity was widespread and abundant. Thicknesses of from 10 to 20 miles of Precambrian sedimentary formations have been studied at various places. This does not mean that at any one locality a sequence of

50,000 to 100,000 feet of Precambrian sediments has been established. It does mean, however, that by piecing together bits of the record from regional studies such a thickness is apparent. The figures merely indicate the order of magnitude of sedimentary formations of Precambrian age. During the Precambrian, there were at least three times of widespread orogeny, or mountain making, and accompanying widespread igneous invasions. Because of universal deformation and extensive intrusions, the early record fades into obscurity, and the *early* Precambrian rocks are often known as the *basement* or *fundamental complex*. This complex is unique in that it is the only sequence of rocks thought to be universally distributed over the surface of the earth. Everywhere on the earth's surface, rocks of the fundamental complex underlie all rocks that have been subsequently deposited except possibly where wiped out entirely by later intrusions which rose from deep within the earth. In contrast to the rocks of early Precambrian, however, except in belts of strong folding, the rocks of late Precambrian are only mildly deformed and are subhorizontal. During the Precambrian, also, many valuable metal deposits were formed, including the great iron formations of the Lake Superior region, which have been the source of approximately 85 per cent of the iron ore annually produced in the United States. Copper, nickel, silver, and gold, as well as other valuable ores, are found in Precambrian rocks.

There is little evidence as to the climates of these early times. It is noteworthy, however, that consolidated glacial deposits indicate that widespread glaciation occurred in the Proterozoic (Middle and Late Huronian). Likewise, indications of Precambrian life are very meager. *Algae, sponges,* and *worms* are certainly known. Indirect evidence of life is found in the iron and carbon content of some Precambrian rocks which in part may have been deposited as a result of organic activity. Certain it is, however, that organic evolution proceeded far in Precambrian time, for at the beginning of the Paleozoic era all of the phyla except the Chordates had evolved.

The greatest area of Precambrian rocks in North America is the shield-shaped region about Hudson Bay. Precambrian rocks are ex-

posed also at places in the Appalachian region, in the Piedmont plateau, in the Ozarks, Wichitas, and Black Hills regions, and at scattered localities in the Cordilleran region. Precambrian rocks are known also on all the other continents.

The Precambrian was brought to a close by local batholithic intrusion, regional uplift and erosion. These closing events are called the *Killarney Revolution.*

***The Paleozoic.*** After a long period of erosion, the Cambrian seas crept in over the continents which had been worn down to a relatively low relief in the erosion interval which followed the Killarney Revolution. On North America, seas first occupied great depressions called geosynclines. One of these, called the *Appalachian geosyncline,* was located along the site of the present Appalachian Mountains; another, called the *Cordilleran geosyncline,* extended along the site of the present day Cordillera; a third, the *Ouachita geosyncline,* extended from Texas to Alabama. These three seaways were more or less persistent features of the Paleozoic landscapes. At times they were filled with water, and at times they were drained They were the loci of the heaviest Paleozoic sedimentation, and in the Appalachian geosyncline about 30,000 feet of Paleozoic sediments were deposited. Because the sediments were dominantly of shallow-water type, it follows that subsidence of a geosyncline about kept pace with deposition, or vice versa. During most of the Paleozoic, a highland area, *Appalachia,* lay to the east of the Appalachian geosyncline. This highland extended an unknown distance into the Atlantic. To the west of the Cordilleran geosyncline was a Paleozoic land area, *Cascadia,* and to the south of the Ouachita geosyncline lay a land mass, *Llanoria.* During the many incursions of Paleozoic seas, the geosynclines were the first and most frequently flooded areas, and from them shallow seas spread out over the interior of the continent. It should be remembered that although marine waters have spread widely over the land areas many times--in the Ordovician, for example, over 50 per cent of the North American continent was flooded—the seas were shallow, probably never more than several hundred feet deep. The shoal depths are shown

by shallow-water features such as ripple marks, cross-bedding, and mud cracks preserved in sediments, and also by the nature of the fossils found so abundantly in Paleozoic rocks of many places.

One feature of Paleozoic geography which deserves particular mention is the vast extent of coal swamps of the Pennsylvanian. Evidently much of the continent stood very close to sea level, and great lowland swamps spread widely through the Appalachian geosynclinal area and in the central states. The rank, luxurious, swamp vegetation formed thick layers of peat which subsequently has changed to coal. Slight oscillations of sea level gave rise to alternating swamp and marine or continental environments. As a result, Pennsylvanian coal beds alternate with other types of sediments.

Not until the end of the Ordovician was there any Paleozoic mountain making in North America and then only a localized development of mountain folding occurred in the Maritime Provinces and New England, accompanied by some volcanic activity. In Maine and the maritime provinces thick lava flows and volcanic ash and breccia beds mark violent Silurian volcanism. In middle Devonian time, a major period of orogeny, or mountain making, occurred in the eastern part of the continent. This was accompanied by both extrusive and intrusive volcanism. In Mississippian time, mountain-making disturbances began in the Ouachita geosyncline, initiating what is called the *Appalachian Revolution* which culminated in the Permian and blotted out forever the Ouachita and Appalachian geosynclines. This geological revolution gave rise to mountain chains which followed the geosynclinal zones of weakness. Presumably the mountains were much grander than those that occupy the same positions today. The mountain folding and faulting of the Appalachian Revolution was accompanied by large-scale intrusion. The continent was uplifted broadly and organisms that had been accustomed to the lowland marine and relatively warm climates of the Paleozoic had either to adapt themselves to the new times or become extinct. Many groups failed to meet the crisis successfully. During much of the Paleozoic, because the lands were low and seas widespread, climatic conditions were prevailingly mild and genial with-

out marked latitudinal zoning, and probably without great seasonal differences. That there were some times of aridity interspersed, however, is shown by thick salt beds. These are evaporation products which represent a Dead Sea condition. With increasing altitude, colder climates resulted and, in North America, at least local glaciation took place in the Permian. In other parts of the world, Permian glaciation was widespread. Africa south of the equator was virtually covered with ice; and parts of Argentina and Brazil, India, and Australia were glaciated at the same time.

In Ordovician and later Paleozoic sediments, where deformation and metamorphism have not been profound, oil and gas have been discovered at many places. Although coal is known in minor amounts in rocks as old as the Devonian, it is from sediments of Pennsylvanian age that the most important quantities of commercial coal are mined in the United States. Salt beds occur in Silurian rocks of New York and Michigan; salt, gypsum, and potash in the Permian beds in the West and Southwest; and lead and zinc in the Cambrian and Mississippian beds of the Middle West.

***The Mesozoic.*** The Appalachian Revolution left North America broadly elevated with respect to sea level. The western Cordilleran geosyncline was drained but only locally deformed. After a prolonged period of erosion, seas again invaded the continent. In the western part of North America, a series of elongate embayments developed from which seas spread over vast areas of the continent, particularly in Cretaceous time. To the east, the geosyncline along the axis of the present Rocky Mountains has been termed the *Rocky Mountain geosyncline.* To the west, inside the Pacific border, there developed another geosynclinal zone of sedimentation. Not until the Cretaceous, however, was there marine invasion of the eastern states, and then only by seas which crept inland from the Atlantic over the submerged oldland of Appalachia, south of Long Island. The Gulf states were also encroached by the Cretaceous seas.

In the Triassic period a peculiar series of elongate fault troughs was formed along the eastern seaboard, which extended discontinu-

ously from the Bay of Fundy to the Carolinas. In the Connecticut valley trough, an estimated thickness of 10,000 to 13,000 feet of bedrock called the *Newark series* was deposited under land conditions. Along the troughs, also, lava flows are associated with the sediments and many basic dikes in the eastern section are thought to be of Triassic age. In the western part of the country, the great coast range batholith, which extends up the Canadian coast 1100 miles northward from the state of Washington, was intruded in the Jurassic or Cretaceous. The Sierra Nevada batholith of California and the Lower California batholith were also intruded in the Jurassic or Cretaceous. These intrusions of Mesozoic times are the greatest since Precambrian. Extensive volcanism was widespread also.

Mild climates prevailed throughout most of the Mesozoic. Distribution of cold-blooded reptiles and of tropical or subtropical types of plants demonstrates the geniality of Mesozoic climate even in high latitude. Red sandstones of eolian deposition in Utah and Arizona and gypsum deposits of the Rocky Mountain states (Triassic) indicate at least local aridity.

The "trap" rocks of Triassic age have furnished much good road metal and concrete aggregate in the eastern states, and the red Triassic sandstone ("brownstone") has been extensively used for building. Associated with the great igneous activity of Mesozoic time in California, rich gold veins were formed, as for example those of the famous Mother Lode district. In the Gulf and Rocky Mountain States, oil and gas are obtained from the rocks of Cretaceous age, and low-grade coal deposits of the same age occur in great abundance in the western interior states, western Canada, and Alaska.

The Mesozoic era was brought to a close by marked diastrophism and volcanism during which the Andes and Rocky Mountains were folded. This great diastrophism is termed the *Laramide Revolution.*

***The Cenozoic.*** The profound physical changes bringing the Mesozoic era to an end caused environmental changes which resulted in a wholesale extinction of many organic groups. With these physical changes, the continents began to take on more modern aspect, and

North America acquired essentially its present size and shape. The great interior seaways of Paleozoic and Mesozoic time had disappeared, and the marine invasions were confined to the coastal areas. The Rocky Mountains of the Laramide Revolution were peneplaned, just as the Appalachian Mountains had been during the Mesozoic. Broad uplifts following the peneplanation and subsequent erosion have given modern form to both the Appalachian and Rocky Mountains. The moist warm climates which had prevailed through so much of the previous history grew progressively though intermittently cooler, and finally an Ice Age resulted. The extent of this late Cenozoic or Pleistocene glaciation is shown in Fig 13-3. The Pleistocene epoch of glaciation consisted of a complicated series of advances and retreats of the ice. At least four major advances separated by interglacial ages of milder climates have been distinguished The duration of the Pleistocene ice epoch was on the order of a million years. With more than 5 million square miles of the earth's surface still glaciated, however, we have not fully emerged from the Ice Age. The continental ice sheet disappeared from the United States between 10,000 and 15,000 years ago.

During the Cenozoic, North America has been intermittently uplifted and eroded. Lâte in the Tertiary, uplifts of the Sierra Nevada Range and the folding and faulting of the Coast Range of California mark what has been called the *Cascadian Revolution.* This revolution is still in progress. All through the Cenozoic, volcanism has been very active along the western part of the continent.

From rocks of the Cenozoic age nearly half of the world's oil supply is obtained. Low-grade coal deposits are found in New Mexico, Wyoming, Colorado, and Montana. Phosphate deposits are worked in Florida, and deposits of the metals such as gold, copper, silver, lead, zinc, and mercury are found associated with Cenozoic igneous intrusions of western North America.

From the preceding brief account of the physical changes undergone by the earth, it may be seen that the earth's surface is not static but is subject to continual changes. Measured in terms of human history, the changes are slight. Over the span of years embraced in


*Modified after U. S. Geol. Survey*

FIG. 13-3. Map of North America showing the approximate extent of Pleistocene glaciation. Note the "driftless" area of Wisconsin.

even a single geological period, however, vast changes have taken place. Between the Precambrian and Pleistocene epochs of refrigeration, other ice ages have occurred. Glacial climates, however, have been exceptional, and during much of geologic time the climate of the earth was certainly more uniform and warmer than at present.

Although the earth has undoubtedly been losing heat by radiation, there seems to have been a compensating internal source of heat. Of the climatic record it can be said that within geologic times, at least, there has not been a progressive cooling. The erosional processes at present are lowering the continents at an average rate of one foot in five to six thousand years. Similar erosional processes have leveled mountain ranges and worn the lands low through many erosion cycles of the past. It is at once evident that were it not for internal energy finding expression in diastrophism and volcanism which offsets the effects of denudation, the land areas long ago would have been reduced approximately, if not entirely, to sea level. What the sources of internal energy may be the geologist is not yet in position to state. Perhaps the most reasonable explanation that can be offered at the present time is radioactive generation of heat. At any rate, the form of the continents was apparently blocked out very early in the Precambrian and in spite of the many encroachments of shallow seas, the continents themselves have been persistently positive. Deep-sea sediments are virtually unknown above the oceanic level, and there is but little evidence of any major transformation of continental areas into deep-sea zones. This is another way of stating that the continental masses and oceanic segments, with only minor exceptions, have been differentiated throughout the geologic record.

## Life

The life record of the earth, as shown by the study of fossils, has given a remarkably clear picture of the interrelationships and evolution of the various animal and plant groups. The fossil record of the Cenozoic era is very full and rather complete. As older and older formations are studied, fewer and simpler types prevail. In the course of evolution, as in the growth of a tree, many branches have been produced. The history of all the higher organisms indicates a backward convergence toward the simpler types, but the connections as yet have not all been established. As already mentioned, the traces of organisms in rocks older than the Cambrian are exceedingly scant. Since, however, representatives of all the phyla except the unicellular

types and vertebrates are found in Cambrian rocks, it becomes certain that life was initiated early in the Precambrian. Table 13.2 gives a synoptic view of the more important invertebrate phyla.

The origin of life is an unsolved mystery, and it is extremely doubtful if the paleontologist will ever discover its solution. It is very probable, however, that the first organisms were of the simplest type, i.e., unicellular structures. At what time in the Precambrian these simple forms originated there is no way of telling, but it must have been very early. Once the unicellular organisms developed, the next step in evolution was for groups of these simple types to remain aggregated rather than separating. Probably the next phylum to develop was that of the Porifera (sponges), which are essentially colonies of individual cells which maintain their own identity, but show some degree of interdependence and cell differentiation. Again the date of origin of this phylum is uncertain. There is some doubtful paleontological evidence that this group had originated before the Proterozoic. In general, fossils of this phylum are poorly preserved.

The next forward step in evolution after colonial habit had been achieved was the development of forms showing a more marked division of labor among the component cells, and in particular the development of a digestive cavity. This phylum, the Coelenterata, includes a number of forms, the best known of which are corals. Presumably, representatives of this phylum had evolved in Precambrian time, but were soft-bodied and hence not preserved as fossils. The oldest fossil representatives of the coelenterates known are Hydrozoa found in rocks of Lower Cambrian age. Fossil corals have been discovered in the rocks of all periods since the Upper Cambrian. Coral reefs are well preserved in some Paleozoic limestones. Rather curious members of this phylum, *graptolites,* have been found to be very useful because of their widespread distribution and because most of the species had a restricted time range. Their recognition therefore permits a close dating of the formation containing them. Graptolites were extinct by the beginning of the Carboniferous.

TABLE 13.2. THE INVERTEBRATES

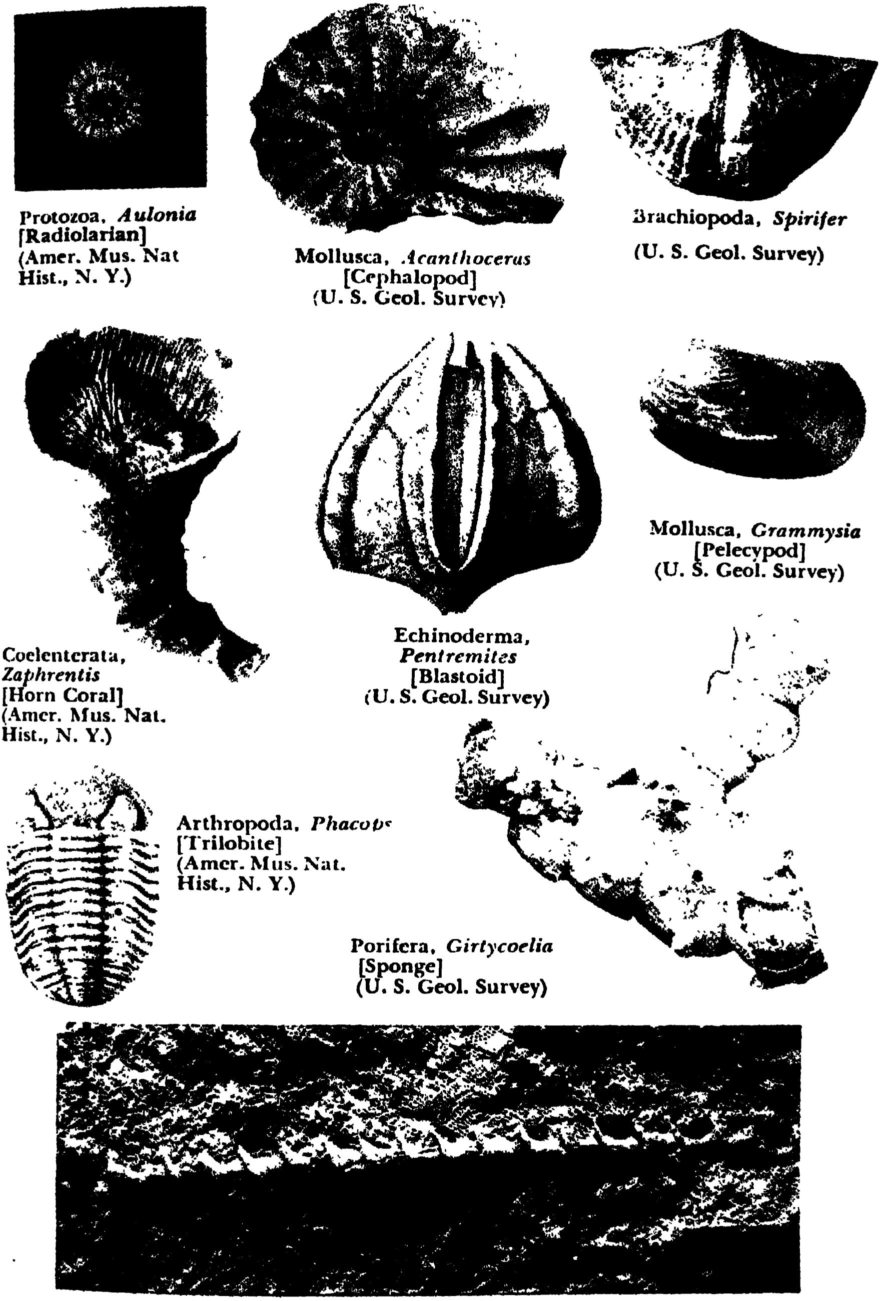
| Phylum | Representatives | Geologic Range | Characteristics |
|---|---|---|---|
| *Protozoa* | Foraminifera; Radiolaria | Precambrian–present | Simplest and most primitive animals. One celled. Found in nearly every environment. |
| *Porifera* | Sponges | Precambrian–present | Many celled, with cells differentiated for special uses. Mostly marine; fixed, usually colonial. |
| *Coelenterata* | | | Aquatic. More advanced than Porifera, possessing definite mouth and stomach. |
| 1. Hydrozoa | Hydra; Obelia | Lower Cambrian–present | Aquatic; mostly marine. Central mouth surrounded by tentacles. |
| 2. Stromatoporoidea | Beatricia; Stromatopora | Ordovician–Devonian | Classification uncertain. Important rock builders. |
| 3. Graptozoa | Graptolites | Upper Cambrian–Mississippian, Esp. Ordovician and Silurian | Classification uncertain. Colonial; marine; separate individuals living in cups on a chitinous stalk. |
| 4. Scyphozoa | Jellyfish | Lower Cambrian–present | Unimportant as fossils. |
| 5. Anthozoa | Corals | Cambrian to present | Differ from Hydrozoa in possession of a short esophagus and body chamber divided into radiating compartments. Most possess either a chitinous or a calcareous skeleton. Marine. Reef builders. |
| *Echinoderms* | | | Marine. Body encased in a calcareous covering, or a leathery skin containing calcareous plates. Spiny. |
| 1. Cystoidea | Caryocrinus | Cambrian–Permian | Usually stemmed. Calcareous plates usually irregularly arranged. Plates pierced by pores. Mouth at top of calyx. |
| 2. Blastoidea | Pentremites | Ordovician–Permian | Short stemmed or stemless. Possesses radial symmetry. Mouth at top. |
| 3. Crinoidea | Sea lilies | Cambrian to present. Esp. Mississippian | Marine. Attached by a stem, or free. Calcareous calyx with bilateral and radial symmetry. Mouth at top. |

| | | | |
|---|---|---|---|
| 4. *Stelleroidea* | Starfish | Cambrian–present | Stemless. Star shaped body with five radiating arms. Mouth on underside. Unimportant geologically. |
| 5. Echinoidea | Sea urchins, sand dollars | Ordovician to present | Organs enclosed in calcareous test, with pentamerous symmetry. Differ from starfish in having no free arms. Stemless. Mouth on underside. |
| *Bryozoa* | Sea moss. Sometimes called moss animals | Lower Ordovician–present | Aquatic, usually marine. Consist of bushy colonies of membranous, chitinous, or calcareous material. Individuals usually microscopic. |
| *Brachiopoda* | Brachiopods. "Lamp shells" | Lower Cambrian–present | Bivalves, with bilateral symmetry. Marine, usually shallow water forms. Attached. Shell chitinous, calcareous, or phosphatic. Abundant as fossils. |
| *Mollusca* | | | Chiefly aquatic. Some land forms. Chitinous or calcareous shells, generally external, but occasionally internal, or absent |
| 1. Pelecypoda | Oysters, clams | Cambrian–present | Bivalves, valves usually equal in size. Shallow water forms. Not well preserved before Pennsylvanian. |
| 2. Gastropoda | Snails | Lower Cambrian–present | Unchambered calcareous shell, coiled in spire. Body divided into head, foot, and visceral sac. In fresh and marine water and on land. Largest group of mollusca. |
| 3. Cephalopoda | Nautilus, squids, octopus | Cambrian–present | Marine. Chambered shell straight, or coiled in one plane. Bilaterally symmetrical. Some possess an internal shell, and some lack a shell. A declining race. |
| *Arthropoda* | | | Animals with transversely segmented body, bilaterally symmetrical. Usually covered with chitinous, or calcareo chitinous external skeleton. Jointed appendages. |
| 1. Crustacea | Trilobites (Cambrian Permian), crabs, ostracods, barnacles lobsters | Cambrian–present | Aquatic. Mainly carnivorous, external skeleton of chitin, or chitin with calcium carbonate or calcium phosphate, divided into 3 parts—head, thorax, abdomen. |
| 2. Insecta | Grasshoppers, bees, ants | Mississippian–present | Six-legged, air breathing, body divided into head, thorax, and abdomen. Skin hardened by chitin. |
| 3. Arachnida | Spiders, scorpions, horseshoe crabs | Cambrian–present | Body of 2 distinct parts cephalothorax and abdomen. Six pairs of appendages on cephalothorax. |

The next major evolutionary advance, which may also have been made in the Precambrian, was the development of a body cavity with the digestive tract within it. What the earliest representative of such a form was we do not know from the fossil record, but following this improvement came the rise of all the higher phyla. Cambrian rocks have yielded fossil mollusks, brachiopods, echinoderms, arthropods, and worms, all of which possess such a body cavity. Representative fossils of the various phyla so far mentioned are shown in Fig. 13-4.

One of the real missing links in the evolutionary chain is the connection between the backboneless forms mentioned in the preceding discussion and the vertebrates. At just what time and under what circumstances a backbone developed is unknown, and various invertebrate ancestors have been hypothecated for the vertebrates The worms, the arthropods, and the echinoderms have all been suggested as possible ancestors The earliest forms which appear to be closely related to vertebrates are the *ostracoderms* which had no internal skeleton but had external bony plates covering the fore part of the body, with a fish like rear end. These have been found in Ordovician rocks and were ancestral to the true fish.

By Devonian time, fish had become numerous and the Devonian is often called the age of fishes. One group of the Devonian fishes had paired fins with segmented supports which were arranged in a manner similar to the bone structure of the vertebrate leg. This group of fishes, *crossopterygians*, is thought to have been ancestral to the amphibians. The air sac or swim bladder was modified into a lung. Indeed, there are three modern species of lung fish capable of breathing, one in Africa, one in South America, and one in Australia. The modification of the crossopterygian fins into legs and swim bladder into lung evidently took place in the Devonian. The first amphibian is represented only by a footprint, Fig. 13-5, left on a mud flat of upper Devonian age. This partial emergence of the vertebrates was an important evolutionary event; it is at least interesting therefore to inquire into the urge for land life. Raymond's



Protozoa, *Aulonia* [Radiolarian] (Amer. Mus. Nat Hist., N. Y.)

Mollusca, *Acanthoceras* [Cephalopod] (U. S. Geol. Survey)

Brachiopoda, *Spirifer* (U. S. Geol. Survey)

Coelenterata, *Zaphrentis* [Horn Coral] (Amer. Mus. Nat. Hist., N. Y.)

Echinoderma, *Pentremites* [Blastoid] (U. S. Geol. Survey)

Mollusca, *Grammysia* [Pelecypod] (U. S. Geol. Survey)

Arthropoda, *Phacops* [Trilobite] (Amer. Mus. Nat. Hist., N. Y.)

Porifera, *Girtycoelia* [Sponge] (U. S. Geol. Survey)

Bryozoa, *Archimedes* and *Fenestellids* (Amer. Mus. Nat. Hist., N. Y.)

FIG. 13-4.

comments on possible causes for emergence are pertinent.[1] Enemies in the water may have driven the crossopterygians to seek refuge on the land. They were, however, the largest and most formidable carnivores of their time Food on the lands may have tempted them, but they could scarcely have been conscious of its existence and in any event they were carnivorous The need for oxygen may have been another cause which impelled them to seek a new mode of life As Raymond suggests [2] ". . . fish inhabiting the constantly changing

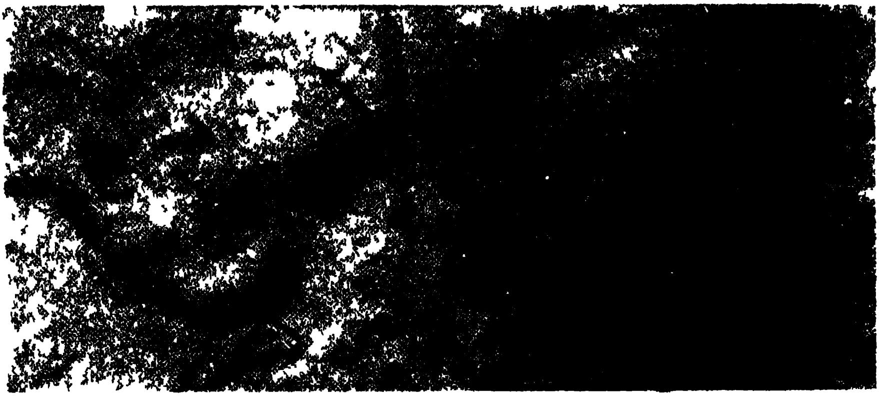


FIG 13 5 *Thinops*-fossil footprint of the earliest tetrapod? (Devonian) Natural im print on the right, plaster cast on the left (Courtesy of Carl O Dunbar Yale Peabody Museum)

waters of an alluvial fan would doubtless be routed from their homes by sudden changes in channel, to be left flopping about in shallow water as streams spread over a flat Those best able to travel by means of fins might win their way to deeper pools A premium was placed on activity, the weak and unlucky were weeded out The instinct for overland migration to other and fresher waters may early have been developed under such precarious conditions of life."

During the Mississippian and Pennsylvanian, amphibians prospered and multiplied in numbers and species With minor structural changes and the development of a type of egg which could be laid on land, the amphibians gave rise to reptiles The liberation of

[1] Raymond, P E, *Prehistoric Life,* Harvard University Press, Cambridge, 1939, pp 101 103

[2] *Ibid*, p 102

Fig 13-6 Mesozoic land reptiles (From the painting by C. R Knight, courtesv of the American Museum of Natural History, New York)

this group from the necessity of returning to water to lay their eggs occurred some time in the Carboniferous. The reptiles were able to survive the Appalachian Revolution and one branch of the group became dominant creatures of the Mesozoic era, the terrible lizards, or *dinosaurs*. The dinosaurs differentiated into a great many species, some of which were small forms, no larger than a cat or dog, others reached the gigantic proportions so commonly associated with the term dinosaur. Perhaps the most ferocious animal species ever to walk on the earth was *Tyrannosaurus rex* (Fig. 13-6), who lived in the Cretaceous. He reached a length of nearly 48 feet, walked on his hind legs, and stood 19 feet high His head, which was approximately 4 feet long by 3 feet high and nearly 3 feet wide, was provided with a battery of sharp, curved teeth from 3 to 6 inches long He was further armed with great claws 6 to 8 inches long However interesting and spectacular the dinosaurs were, they nevertheless traveled a dead-end route and were extinct before the beginning of the Cenozoic. Other Mesozoic reptiles took to the air (Fig 13-7), and still others occupied the seas (Fig. 13-8).

FIG. 13-7. Mesozoic marine reptiles. (From the painting by C. R. Knight, courtesy of the American Museum of Natural History, New York)

Fig 13 8. Mesozoic flying reptiles (From the painting by C Astori, courtesy of the American Museum of Natural History, New York)

The reptiles of the Mesozoic achieved two notable successes, however; they gave rise to the birds and mammals. The earliest known bird, *Archaeopteryx,* demonstrates its primitive character by its tooth-bearing jaws and its segmented tail The earliest mammals also had reptilian characteristics and habits and were rather insignificant members of the animal community in which they found themselves. The oldest mammals apparently originated in the Triassic. With the elevation of the continents during the Laramide Revolution, and the increasing rigor of climate, the cold-blooded reptiles experienced a terrible setback, and the hitherto humble mammals of small size and brain experienced a period of rapid evolution and prosperity. The *primates,* of which man and his cousins the lemur, monkey, gibbon, and apes are modern representatives, probably originated in the Cretaceous, for primate fossils have been found on all the continents except Australia, in rocks of the earliest Cenozoic Because of their habits, however, they have left a rather scanty fossil record. Man (Fig 13-9) himself appeared on the scene quite late in the Cenozoic His chief distinguishing characteristic was his proportionately large brain. As far as the fossil record shows, no undoubted human remains date back beyond the Ice Age. Artifacts, however, indicate a somewhat earlier man. Compared with the span of time during which other groups have held sway in the geologic past, man is just at the threshold of his earthly career. He

FIG. 13-9. *Pithecanthropus erectus.* (American Museum of Natural History, New York)

is involved in an evolutionary struggle to achieve racial sanity and a truly human status, however, and may destroy himself in the struggle.

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Spence Air Photos

ELYSIAN PARK SLIDE, CALIFORNIA.

# CHAPTER XIV

# GEOLOGIC MAPS

Many engineering projects are preceded by geological investigation, the reports of which must be read and understood by engineers in order to take advantage of the information discovered. One essential part of a geological report is the map. Whether the engineer himself will be called upon to prepare such geological reports and maps or not, ability to digest and interpret them is an essential part of an engineer's geological training. For problems of engineering that require or are assisted by geological information—tunneling, water-supply, sanitary systems, bridge and dam formations, reservoir basin studies, erosion controls, sources of construction materials, building sites, and many others—geological maps and sections supply essential data. To make best use of geological maps, the engineer should be able to read from the map what is reasonably certain and what is surmise on the part of the map maker. He should be able, also, to construct geologic sections in any desired directions, and to determine from the map and sections certain quantitative lithologic and structural data. The following discussion of geologic maps attempts to answer three fundamental questions: What is shown? How is it shown? and How can the maps be used?

## Types of Geologic Maps

Four types of geologic maps include those most generally used. These are (1) *surficial maps*, (2) *outcrop maps*, (3) *areal maps*, and (4) *structural maps*.

***Surficial Maps.*** Surficial geological maps show the character and distribution of the various types of surficial materials. Agricultural soils maps are really a form of surficial geological maps, but at the hand of the agriculturally trained soils surveyors so many local soils types and series have been established that requisite engineering data are difficult to read from most of the agricultural soils maps, and geological data are more or less obscured. Anyone concerned with the engineering aspects of soils, however, should acquaint himself with the agricultural soils maps and with methods by which those maps are constructed. Geologic surficial maps that differentiate the types of surface material according to geological categories, as stream gravels, stream alluvium, glacial-marine clays, glacial gravels, and the like, are the most useful in engineering work, for from them distribution, areal extent, and characteristics of many deposits can be inferred. Within the glaciated regions, these surficial maps are of especial interest to the engineer. Surficial maps are particularly useful aids in the search for construction materials, and in guiding certain other types of engineering work, for example, drainage and water supply studies, airport and highway locations, and other similar endeavors. Because of local variations in composition, thickness, and distributions which may not appear on maps of relatively small scale, observational checks, test pits, borings, and soundings should be made in the field to supplement these maps. Fig. 14-1 shows a portion of a surficial geology map.

***Outcrop Maps.*** An outcrop map shows the areas where ledge, or bedrock, is exposed. The rock types are differentiated, and structural data are usually indicated on the map. Because many outcrops are of small extent, outcrop maps must be of moderate or large scale. It is always convenient in using a map to know where the bedrock exposures can be found. For engineering use in particular, outcrop maps are valuable. An example of use is the location of road metal: if a certain quartzite is known to outcrop at specific localities, much time and effort can be saved in choosing a suitable quarry site by going directly to the outcrop areas, guided by the outcrop map.

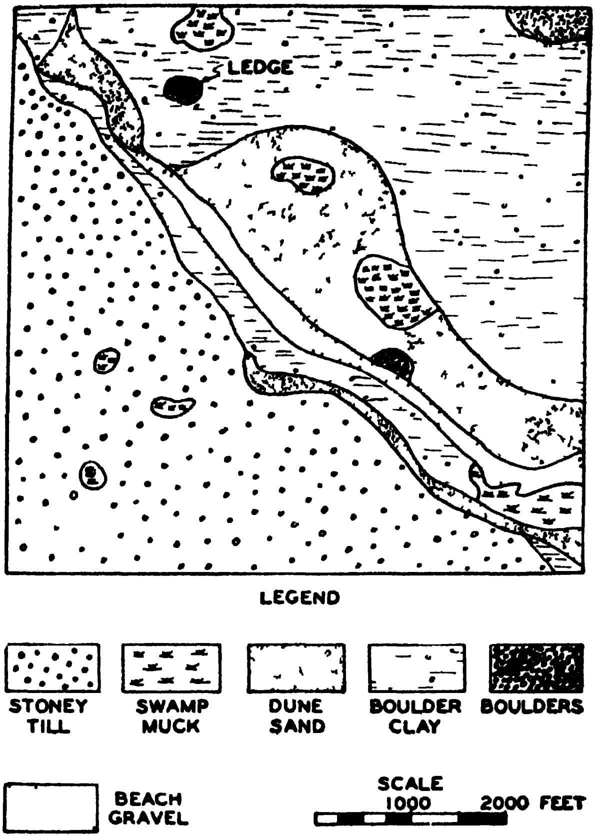



Fig. 14.1 Surficial geology map

***Areal Maps.*** Areal geologic maps (area maps) are plan views of the geology. They show both the observed distribution of geologic units or formations mapped and also the inferred distribution beneath the soil and vegetation cover as if the latter were swept entirely away. In some areas, because of complex structure and few exposures, extrapolation of observed boundaries of rock types is little better than guesswork. In other areas, the distribution of concealed formations may be closely inferred by study of soils, topography, vegetation, and by the structural requirements. On maps of large or moderate scale, the advantages of both outcrop maps and areal maps may be combined by indicating the outcrop areas, or

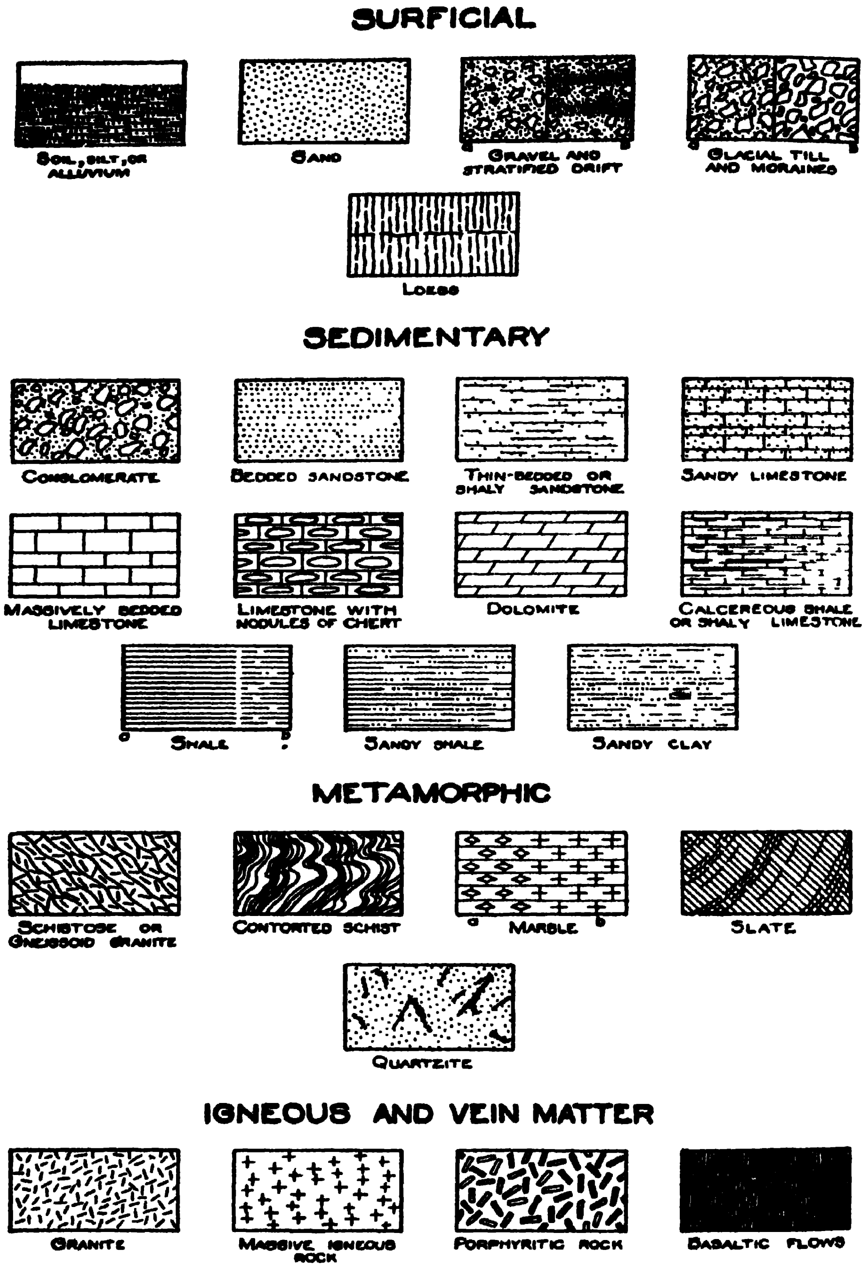



Fig. 14-2. Conventional lithologic symbols. (U. S. Geological Survey)

places where outcrops are especially numerous, by differences in the shade of color or weight of pattern. Recent colored maps of the Canadian Geological Survey have used this device to good advantage.

The differentiation of materials mapped can be shown by several methods. The two most commonly used devices are patterns and colors. Usage in patterns varies, but the standard or conventional symbols used in geologic sections by the U. S. Geological Survey are also adapted to plan and are used on many black and white maps. These conventional symbols are shown in Fig. 14-2. It will be noted that, in general, the symbols for sedimentary rock types consist of dots or straight lines; for metamorphic rocks, wavy lines; and for igneous rocks, checks, crosses, or rhombic patterns. So far as practicable, it is desirable to depict the structural trends of the rock units by the arrangement of the map symbols, as illustrated in Fig. 14-3.

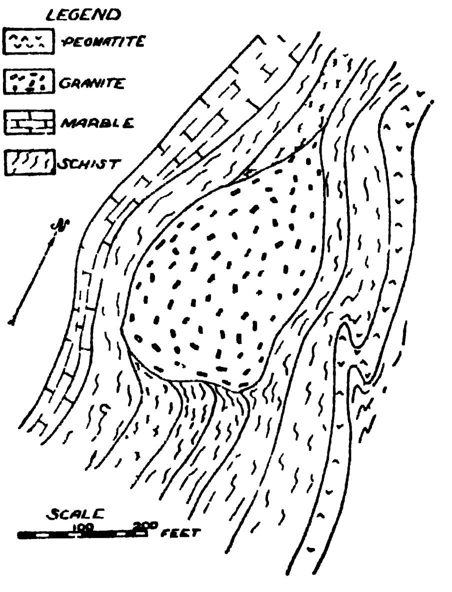



FIG. 14-3 Portion of a geologic map.

Such an arrangement shows at a glance the broad outlines of structure.

On the maps of the U. S. Geological Survey and of many other organizations, colors are used to represent the geologic periods. Sym-

bols (letters) are also used to designate the ages. The periods arranged in order of increasing age from the top down, with the conventional symbols, are shown in Table 14.1.

TABLE 14.1. CONVENTIONAL AGE SYMBOLS FOR AREAL GEOLOGIC MAPS

| *Period* | *Symbol* |
|---|---|
| Pleistocene and recent | Q |
| Tertiary | T |
| Cretaceous | K |
| Jurassic | J |
| Triassic | TR |
| Permian | P |
| Carboniferous | C |
| Devonian | D |
| Silurian | S |
| Ordovician | O |
| Cambrian | Є |
| Algonkian | A |
| Archaean | AR |

Overprints of patterns represent the individual rock units of mapping, which are called *formations*. A formation consists essentially or predominantly of one type of rock or of more or less uniformly varying or alternating rock types. Formations may be composed of several *members*, but the formation itself is essentially a lithologic unit. Formations are generally given local names from the locality of best exposure. On maps, the period symbols of Table 14.1 are combined with lower case letters denoting the particular formation, thus: *Dol*, D for Devonian, *o* for Onondaga the name of a widely outcropping Devonian limestone, and *l* for limestone. The legend of the map gives a key to the colors or patterns of the formations depicted, and it states their lithology. The legend, incidentally, also shows the historical sequence of formations, for they are arranged in the legend in age sequence with the oldest formation at the bottom.

***Structural Maps.*** Many areal geology maps include structural symbols superposed on the patterns or colors representing the lith-

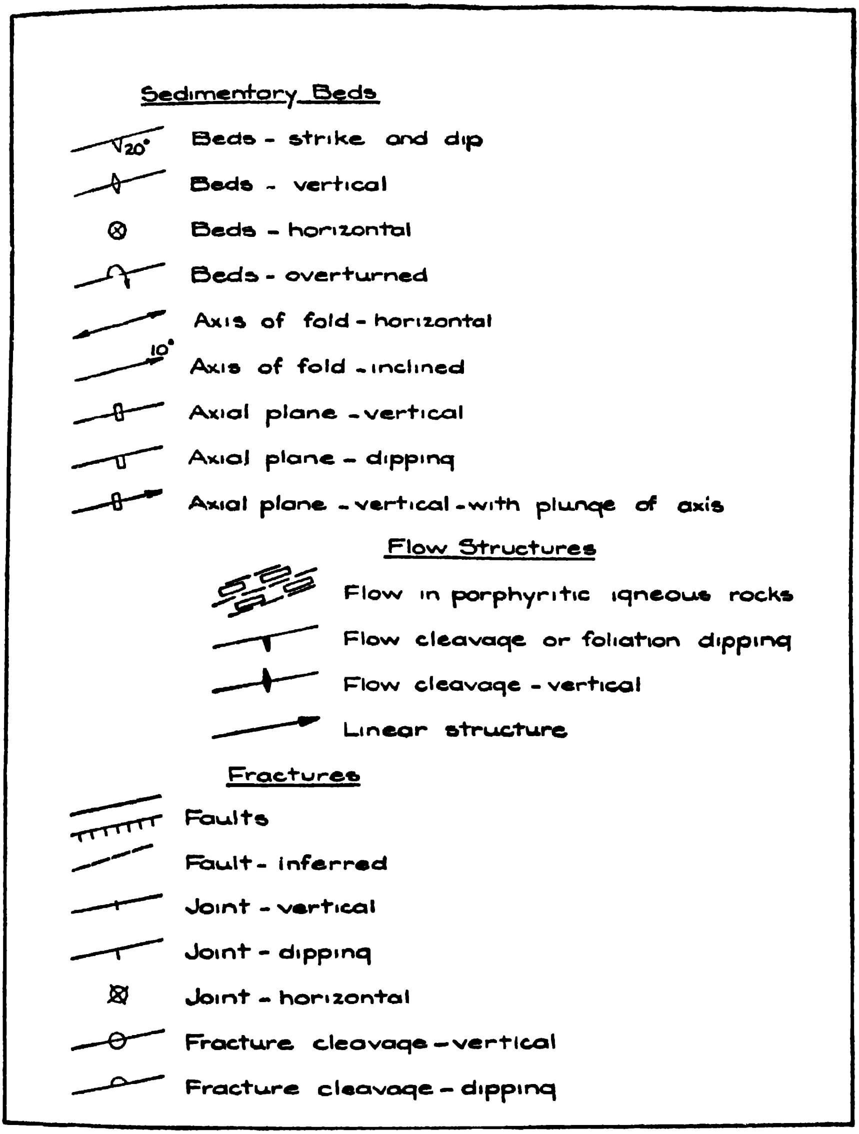



FIG. 14 4 Conventional structural symbols

ologic units. Where the structure is simple and there are but few structural observations recorded, this combination is helpful for quick comprehension of the geology. In complicated areas, however, or where a wealth of structural detail has been accumulated, separate structural maps are more satisfactory. This is particularly desirable if the rock units are represented by symbols in black and white. A variety of methods are used in representing geological structure on maps. The two most commonly employed are structural symbols and structural contours.

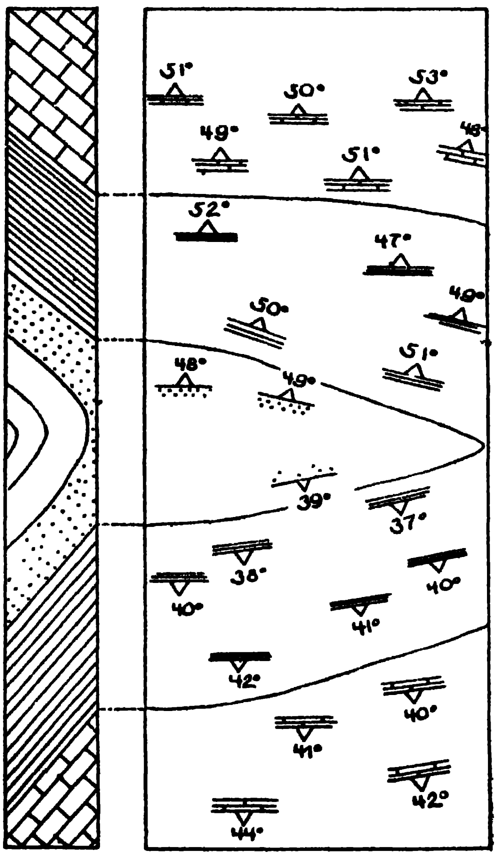



FIG. 14-5. Geological map showing structure by symbols.

*Structural Symbols.* Individual field observations are plotted onto the map. The more complex the structure of the region mapped, the greater the number of observations necessary to delineate structure. It is frequently helpful to draw large symbols on the map that generalize the individual observations. Although there is no standard or universally used system of structural symbols, those shown in Fig. 14-4 are used by many geologists, with various modifications according to the individual preferences. Because this type of symbol is not standardized but varies according to convenience and taste, every structural map carries an appropriate legend indicating the usage. Fig. 14-5 shows a structural map using symbols. Note that, whereas the strike or trend of the mapped structures is plotted onto the map by protractor in correct azimuth, the inclination values must be indicated by figures. If the inclination values are omitted, it is impossible to construct accurate cross sections from the map.

*Structural Contours.* In regions where deformation is not too great and sufficient data are at hand, structure is often portrayed by means of structural contours drawn on the top or bottom of some

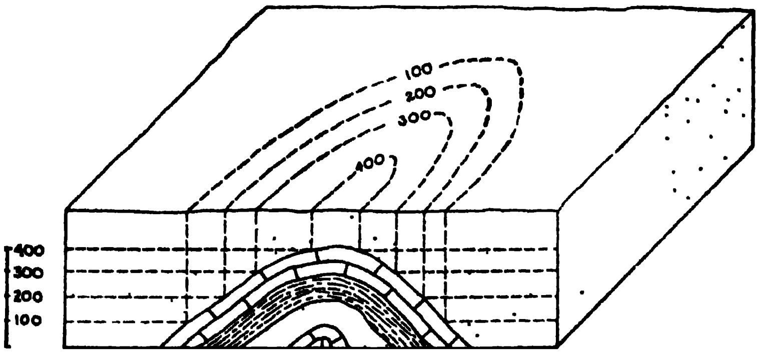



FIG. 14-6. Geological structure shown by structural contours.

bed, a specific "horizon," recognizable in the field or from available drill records. Fig. 14-6 illustrates a dome shown by structural contours. Petroleum geologists in particular have made effective use of structural contour maps.

## USE OF GEOLOGIC MAPS

When a student asks, What's the use of a transit? two types of answer can be given. One answer might list specific applications, for example property surveys, highway surveys, map-making, construction control, and so on. A second answer takes a considerable part of the usual semester course in surveying, and explains the use of that instrument in measuring horizontal and vertical angles, and in determining elevations and distances. It is in this sense of *use* rather than *application* that the following brief discussion answers the question, What's the use of a geologic map?

From well-constructed and accurate geological maps, certain structural inferences, geological sections, block models, and three-dimensional diagrams can be made for which many diverse applications are found in engineering practice. If the geologic map is on a contoured base the range of inference is increased and certain quantitative values can be established. Topographic-geologic maps are accordingly more useful than the uncontoured maps. Two interrelated lines of map evidence serve as the basis of geologic map interpretation. These are (1) the topographic-geologic relationships and (2) the areal distribution patterns. From these two approaches, structural attitudes, sequence of strata, thickness of beds, and presence of structural discordances can qualitatively or quantitatively be worked out. Formation boundaries not exposed in the field often can be geometrically located thus completing an otherwise unfinished map and extending its usefulness.

*Contour-Contact Relations.* If both geologic and topographic mapping are good, much can be learned from the study of the map. In the following discussion two basic assumptions are made. First, it is assumed that within a limited part of the map the geologic features studied are plane surfaces, bedding planes, fault planes, or the margins of igneous masses. This assumption is not fully justified, as no one of the features is a mathematical plane. Over short distances, however, the considered surfaces approximate planes, and little error is introduced if good judgment is exercised in making

the assumption. Inasmuch as these geologic surfaces are not true planes, the map points taken for reference should be closely spaced and not chosen from widely distant parts of the map. The second assumption made in this type of map study is that the map is correct, and the contour lines represent the intersection of equally spaced horizontal planes with topography. If every point on a contour line were at the same elevation, as called for by definition of a contour, and if geological observations were correct and exactly located, the assumption would be perfectly true. For well-made maps, little error is introduced by this assumption. With these two assumptions, then, the geological problems of dip, strike, and thicknesses reduce to the solution of geometrical plane relationships and plane intersections, familiar to every engineer through the medium of drafting-room practice.

*Strike.* Strike is defined as the direction of the line of intersection of a horizontal plane with the considered plane surface, i.e., bedding plane, fault plane, dike wall, or other surface. The strike of a sedimentary bed, therefore, is the *direction* of a level line on the bedding plane. On any inclined plane surface, horizontal lines can be drawn spaced at equal vertical intervals apart. Projected to a horizontal plane (map), these lines are called *strike lines.* They depict strike and dip of the inclined plane, just as contour lines on a topographic map depict direction and slope of a valley wall or other topographic feature. If values are given to strike lines, as they are to the contour lines of topographic maps, with reference to elevation above or below sea level, they are called *structural contours.* Structural contours are merely contour lines which represent some particular geologic structure rather than ground surface. If the strike of the structure changes, as in folded beds for example, the structural contours are curved lines on the map; if the dip (slope) changes from place to place, the structural contours on the map are spaced either more closely together or farther apart according to whether the change in dip is an increase or decrease of inclination.

The top or bottom contact of a sedimentary formation in a conformable series is shown on geologic maps as a thin black line, which

is really the trace of a bedding plane on the topographic surface; likewise a fault is shown by a heavier map line, which is the trace of the fault plane on the topographic surface. To determine a level line (strike) from the trace of an inclined plane, it is only necessary to find two points of the trace (contact, fault) at the same elevation. Where a contact line crosses a topographic contour line, the elevation at that point is established. Where the *same* contact crosses the *same* contour line again, another point is located, and a line con-

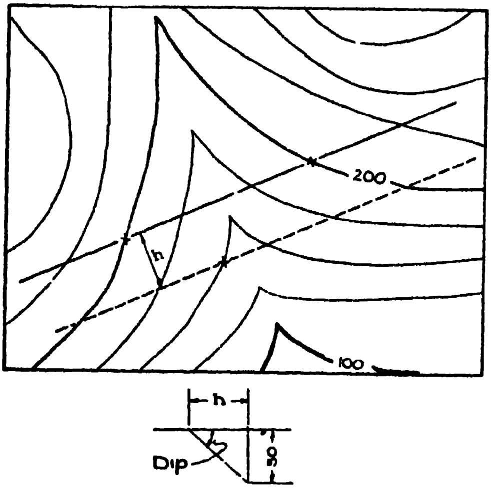



FIG. 14-7. Determination of dip and strike from contact-contour relations. The points designated X are on the same contact.

necting these two points is a strike line, as shown in Fig. 14-7. It should be remembered that the *same* contact, *either* top *or* bottom of the formation, must be used. A common student error is to determine the elevation of a top contact of a formation at one place on the map, and of a bottom contact somewhere else, and connect the two. Favorable places to find two points on a contact at the same elevation, i.e., crossing the same contour, are on opposite sides of a valley or hill. If the structure is uniform throughout the map area, all strike determinations will be essentially parallel.

On some maps, a contour line may not intersect a given contact at two places. In this instance it is possible to determine the strike from any three points of known elevation on a contact. Three points

where contours cross a formation boundary give three points of known (but different) elevation. These are connected to form a triangle. If the dip is uniform, the line connecting the highest and lowest corners of the triangle has a uniform slope, and somewhere along it is a point at the same elevation as the intermediate corner of a triangle. This is the point sought, and it can be found either

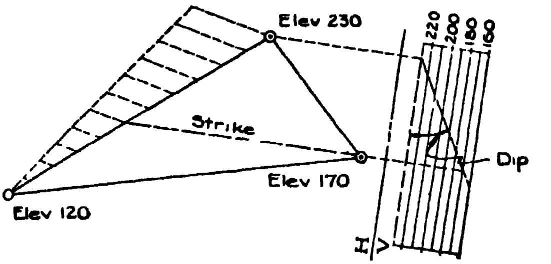



FIG. 14-8 Determination of strike and dip from three points on the same surface at different elevations

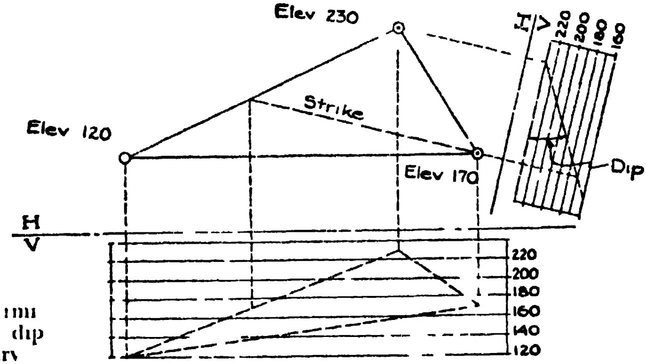



FIG. 14-9 Determination of strike and dip by descriptive geometry

by proportion or graphically. A graphical solution is shown in Fig. 14-8. A line drawn through the two points of equal elevation is a level line, hence a strike line.

Another, and perhaps neater, solution of the strike problem where no two points of a boundary (contact) can be found at the same elevation on the map is shown by Fig. 14-9. The procedure is as follows: construct a random cross section in any direction, but such that the high or low point of the three chosen falls between the other two. The points are projected to the cross section. Next a horizontal line is drawn on the cross section at any elevation that

will cut the triangle The points of intersection of the horizontal line and the triangle are then projected back to the plan, a line connecting them gives the strike

*Dip.* For plane or near plane geological surfaces, neglecting overturn, there are three possible cases of dip (1) the structure is horizontal (no dip), (2) the structure is vertical, dip 90°, and (3) the

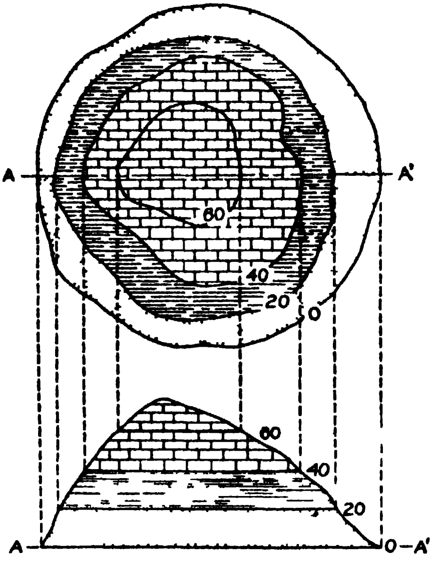



FIG. 14 10 Relation of boundaries of horizontal beds to contours

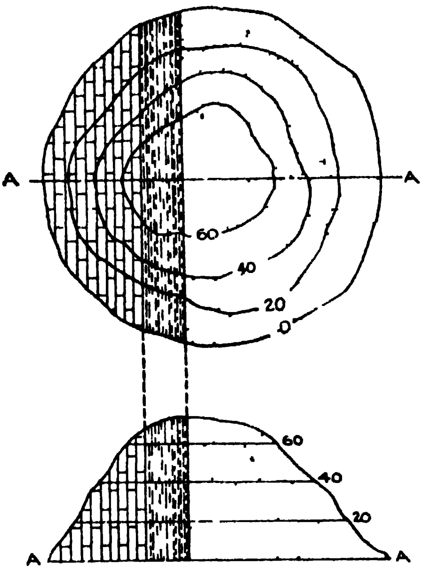



FIG. 14 11 Relation of boundaries of vertical beds to contours

structure is inclined at some angle intermediate between horizontal and vertical.

*Horizontal structures* It is at once apparent, as shown in Fig 14-10, that a horizontal structure will intersect the surface parallel to the topographic contours Few geologic structures are absolutely and uniformly horizontal plane surfaces, and, further, contour lines as well as geologic boundaries are largely sketched within the control limits Absolute parallelism, therefore, is not to be expected

*Vertical structures* If contacts or other structures are vertical the boundaries on the geologic map are not deflected by topography This is shown diagrammatically in Fig 14 11

*Inclined structures.* The next or intermediate case is that of inclined structures. Two possibilities exist here. Either the attitude (dip and strike, or trend and inclination) is uniform throughout the map area or it is not. If the dip and strike are uniform throughout a considerable area, that does not mean that the geologic boundaries will appear as straight lines on a contour base map. On the contrary, structural lines are geometrically determined by the topography, and, unless the dip is vertical or the topography plane, they are never straight. This is simply illustrated by Fig. 14-12 which shows a

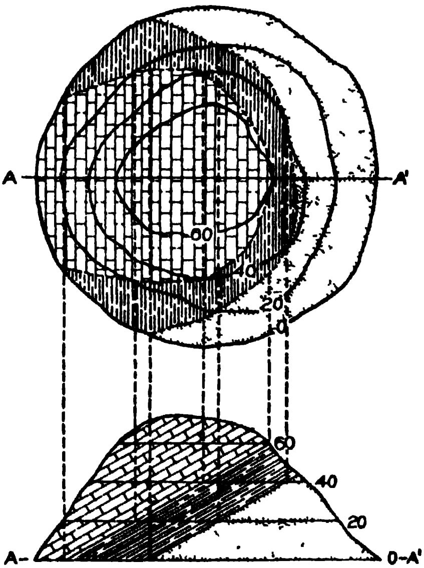



FIG. 14-12 Relation of boundaries of inclined beds to contours.

conical hill traversed by a thin sill of uniform trend and inclination within the area of the map. The lower part of the figure shows a geological cross section. It will be noted in the upper part of the diagram that the hill causes a deflection of the contact lines of the sill, convex in a direction opposite to that of the dip of the sill.

The more steeply the considered structure is inclined, the more nearly straight the map lines which depict it; conversely, the gentler the angle of dip, the more nearly do the structure lines which show

it on the map coincide with the topographic contours. In regions of low dip, the formations in detail show characteristic contour-following tendency. Over a considerable area, however, the broader relations may be seen, and a belted pattern becomes evident.

After the strike is determined, dip is readily solved. A strike line is drawn through the point of intersection of a geologic boundary and a topographic contour. It is a structural contour on the bedding plane at an elevation equal to that of the contour line whose intersection with the boundary determined it, and as with topographic contours, every point on the strike line (structural contour) is at the same elevation. Parallel to this strike line, another of known elevation is drawn through the intersection point of *another* topographic contour and the *same* contact. The map distance (horizontal distance) between the two parallel strike lines can be scaled, which with the difference in elevation between the two structural contours gives the tangent of the dip angle. Or the dip can be solved graphically

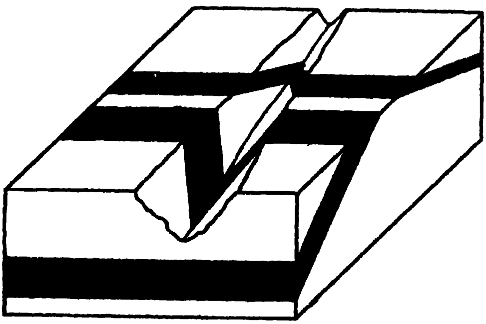


Fig. 14.13. Outcrop V's related to valley.

by drawing a right triangle to scale, with the horizontal leg equal to the horizontal distance between the strike lines, and the vertical leg equal to the difference in elevation between them.

After the strike has been determined, another very simple way to find the amount of dip is to construct a cross section at *right angles to the strike* and to project to it several points from *one* contact. The line connecting these gives the dip which can be measured with a protractor. *Remember in constructing structural cross sections that, unless the horizontal and vertical scales of the cross*

*section are equal, dips and thicknesses of beds shown on it are not true,* but are exaggerated or diminished according to whether the vertical scale is greater than or less than the horizontal scale

It was noted in Fig 14-12 that a hill causes a deflection of a contact—convex away from the direction of dip It will be noted on detail maps that the boundaries of plane or near plane structures show deflections in valleys that give a V pattern Unless the valley gradient is steeper than the dip of the structure in the same direction, the V in the valley points down dip, as shown in Fig 14 13 Gentle dips give rise to long V's, and conversely short V's indicate steep dips There is, of course, no V if the dip is vertical The scale of the map, however, must be considered in judging the length of V's For example, on a map with a scale of 1/12,000 a bed dipping 45° should have a V 0 1 inch long in a valley 100 feet deep On a scale of 1/62,500, this would give a V approximately 0 02 inch long, too short to represent.

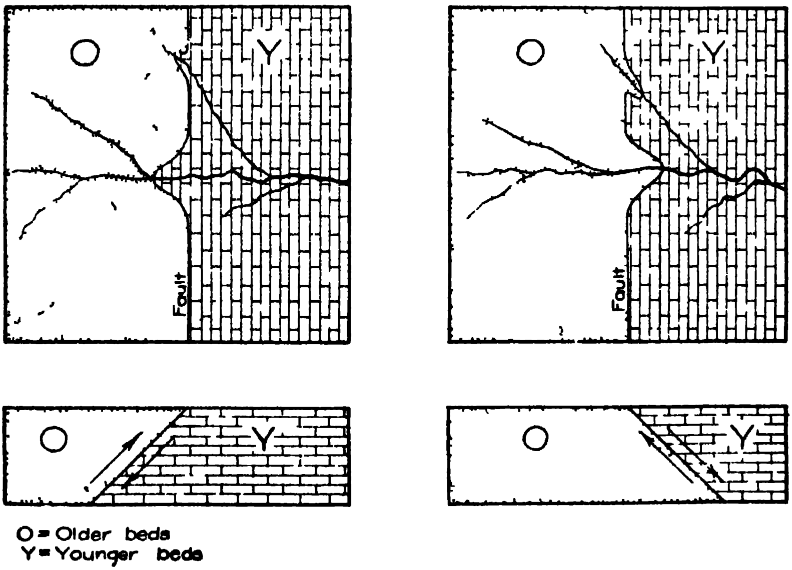



FIG. 14 14 Apparent deflection of fault trace in valley *left* reverse fault, *right,* normal fault

*Completion of Geologic Boundaries* Field exposures are never

complete enough to permit the drawing of geologic boundaries without considerable extrapolation. The extension of contacts based on field evidence is briefly discussed in the chapter on field methods A geometrical analysis of the map frequently aids in completing the extrapolation of concealed formation boundaries of inclined beds or other geologic structures. The geometric requirements of topography and structural attitude also serve as a check on field inference and help direct field traverses into the critical zones. One of the methods for completion of the geologic map is illustrated in the following example. Fig. 14-15 shows a series of exposures of sedimentary beds of approximately uniform strike and dip within the map area. In order to complete the map, formation boundaries must be drawn. The first step is to construct a cross section at right angles to the strike of the beds with a *vertical scale equal to the horizontal scale* of the map. Distortion of dip and thickness of the beds is avoided by using the same vertical as horizontal scale The next step is to project the geologic data from the map (plan view) to the cross section. These data are plotted on the elevations of the cross section corresponding to those of the map The cross section is completed by drawing in the formation boundaries, as required by the distribution of the several rock types on the cross section. This is illustrated on the cross section of Fig. 14-15. With the formation boundaries or contacts completed on the cross section, the next step is to project these contacts to the map. For example, wherever the projection line from the intersection of the sandstone-overlying rock boundary and the 50-foot elevation line on the cross section cuts the 50 foot contour line on the map, a point on the contact is established Moving up the dip, next, to the 60-foot elevation of the same contact on the cross section, it will be noted that wherever this projection cuts the 60-foot contour line of the map, additional points on that boundary are established. Following the same procedure, other points on the contact are established on the map, and the line connecting these map points is the most accurate geologic boundary between the sandstone and overlying rock that can be drawn from

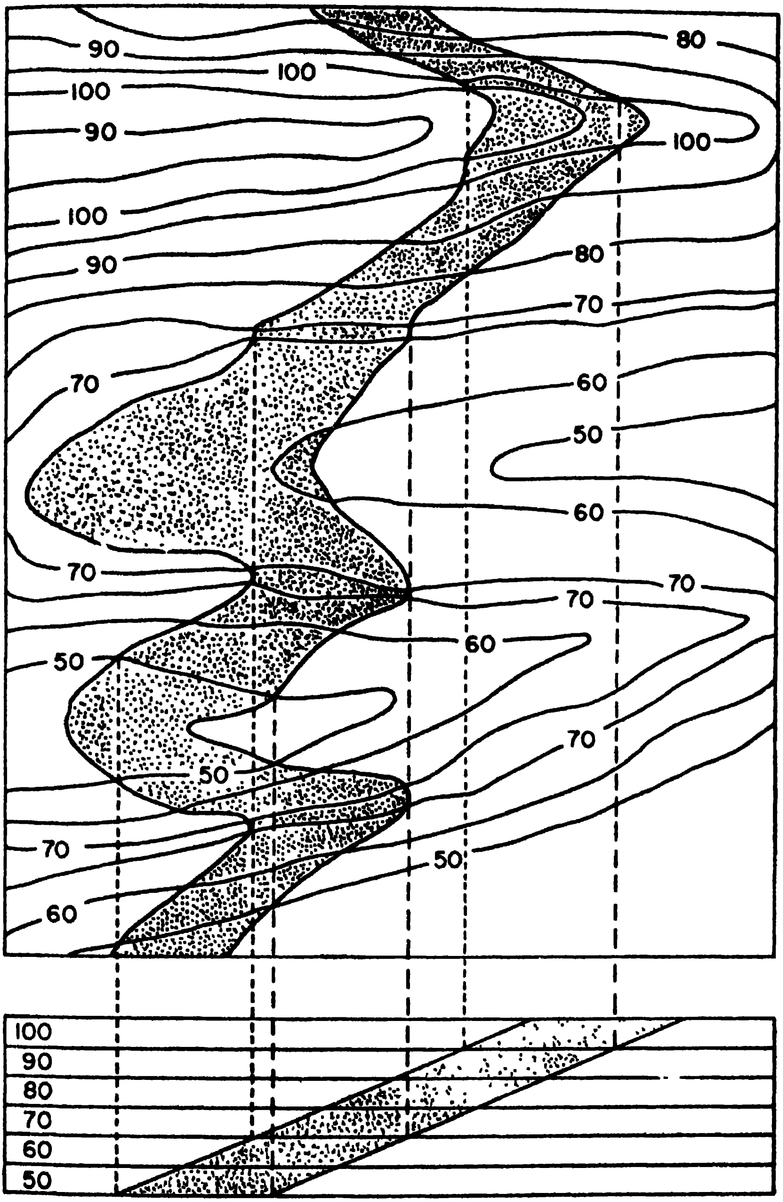



Fig. 14-15. Completion of formation boundaries of uniformly dipping beds.

the available data. The contact at the base of the sandstone is similarly established.

Where the geology is more complicated, it may be necessary to use two or more cross sections in completing the geologic plan. If, for example, the course of a dipping dike was to be plotted from several observations onto the map of Fig. 14-15, it would be necessary to construct a cross section normal to the strike of the dike and then to project top and bottom contacts of the dike to the map. Cross sections normal to each of two series of unconformable beds of different structural attitude would be necessary to complete the areal map of such an area, and other complications could be cited.

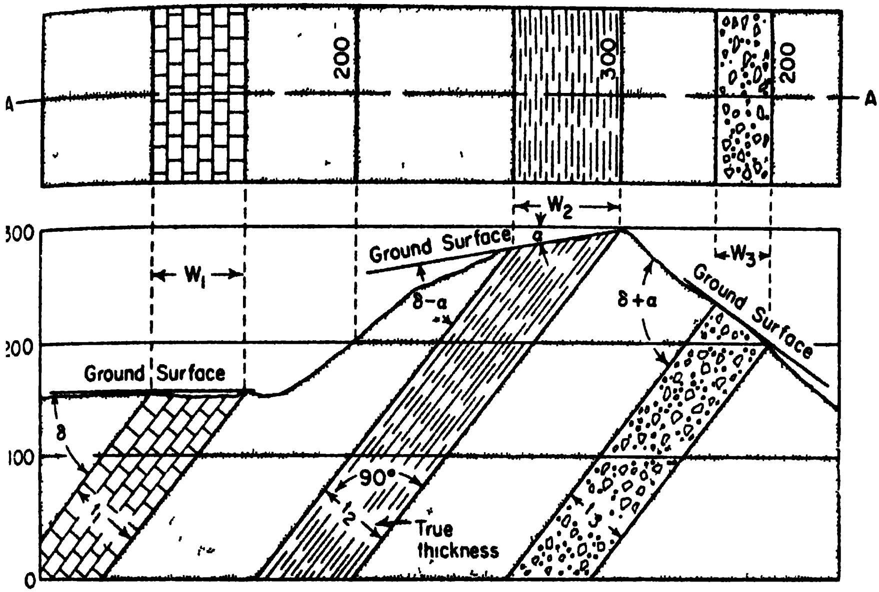
*Thickness of Beds.* The thickness (Fig. 14-16) of a dike, sill, or sedimentary bed can be approximated from geologic-topographic maps. If the beds are horizontal or vertical, thicknesses are taken directly from the map. For inclined beds, calculation is necessary

Horizontal beds and sills have contact lines parallel to the topographic contours, as already pointed out. By interpolation between the contours, therefore, reasonably close values are obtained for thickness. Large-scale maps with small contour intervals give the most accurate results.

The thickness of a vertical bed or dike can be determined by scaling the map distance perpendicularly from one contact to the other. Caution is needed, however, in this determination on maps of moderate and small scale. For example, because of economic or geologic significance, some beds and dikes are shown on maps of a 1/62,500 scale which actually are too thin to show on that scale map. From the map some might be estimated to be 40, 50, or 100 feet thick, whereas they actually may be but 5, 10, or 15 feet thick. Because all distances shown on maps are horizontal distances, the thickness of an inclined bed may be calculated by measuring the extent of the bed perpendicular to the strike and multiplying by the sine of the dip angle. The true thickness ($t$) is thus:

$$t = \text{width of bed} \cdot \sin(\text{dip angle}) \quad \text{(see Fig. 14-16)}$$

These determinations are no more accurate than the map measure-




$W_1 = t_1 \cdot \cos\ \delta$ $W_2 = t_2 \cdot \operatorname{cosec}(\delta - a) \cdot \cos a$ $W_3 = t_3 \cdot \operatorname{cosec}(\delta + a) \cdot \cos a$

FIG. 14 16 The true thickness of beds

ments necessary for their solution. The quickest and most direct solution is graphical. A geologic cross section at right angles to the strike is constructed with horizontal and vertical scales equal; the thickness of the bed is then scaled from the cross section Inasmuch as field measurements are commonly slope distances, thicknesses may be calculated from *field data* as also shown on Fig. 14-16.

It is worth while to emphasize an apparently simple point here, but one that is frequently overlooked. The width of exposure of a tabular-shaped body of rock depends on three factors: the angle of dip of the rocks, the topographic slope and its direction, and the thickness of the tabular body of rock. Either in ignorance of this principle or forgetful of it, some have opened up quarries on "huge bodies" or "mountains" of the rock, which on development prove to be thin sheets, dipping nearly parallel to the topographic surface.

***Lithologic Distribution Patterns.*** Much structural information is shown by map (or field) distribution of rock formations. The

details of lithologic distribution patterns are due to the effects of topography, as has been shown. However, on level or near level surfaces, structure determines the formation patterns, and in regions of topographic diversity, the broader features of rock type distribution are structurally controlled. From these regional patterns of rock type distribution, therefore, horizontal or low-dipping beds, folds, faults, and unconformities can be recognized.

*Horizontal Rocks.* The boundaries of horizontal beds or those of low dips, as has already been pointed out, follow the contours. The regional pattern of formation boundaries, therefore, is *dendritic* or tree-like, and the trends of geologic boundaries simulate topographic contours. Such a dendritic pattern is shown in Figs. 14-17

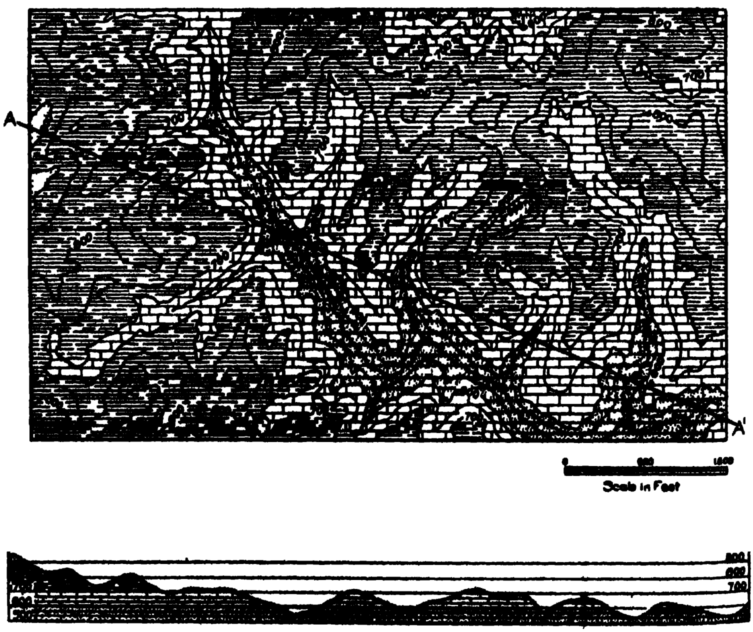



Fig 14-17. Geologic map of horizontal beds showing dendritic outcrop pattern.

and 14-18. Even though both contour and drainage lines are omitted from the map, if the area is stream dissected, the dendritic distribution pattern is strikingly apparent. On broad, gently inclined plains,

horizontal or low-dipping beds appear as belts or bands. Examples of the belted pattern are shown on the small-scale geologic maps of the Gulf and Atlantic coastal plains of the United States.

FIG 14 18 Aerial photograph showing horizontal beds. The view shows cherty limestones, clay shale, and some sandstone. The cherty beds, comparatively resistant, form the narrow white bands that mark the outcrop The easily weathered shale assumes low slopes and appears as broad dark bands (Courtesy of U. S. Dept. Commerce, Civil Aeronautics Administration)

*Folds.* Rocks composing eroded folds outcrop in belts or bands. Thus because of the folding and erosion, the same formation may appear on the geologic map as separate belts or bands. If two belts representing two limbs of a fold are parallel, the fold axis is horizontal; if they converge, the fold axis is inclined. If the structure is an eroded anticline, the plunge is in the direction of the convergence of the limbs. If it is an eroded syncline, the plunge is in the direction of divergence of the limbs. In other words, plunging anticlines close in the direction of plunge, whereas plunging synclines open in that direction. If the relative ages of the beds are shown in the map legend, anticlines and synclines can be distinguished by the relative position of the older beds. If the older beds outcrop inside the younger ones, i.e., towards the center of the fold, the structure is anticlinal. If the younger beds outcrop inside the

bands of older rock, the structure is synclinal. Figure 14-19 illustrates this principle. In the same figure the use of the outcrop V's in the stream valleys leads to the same structural conclusion.

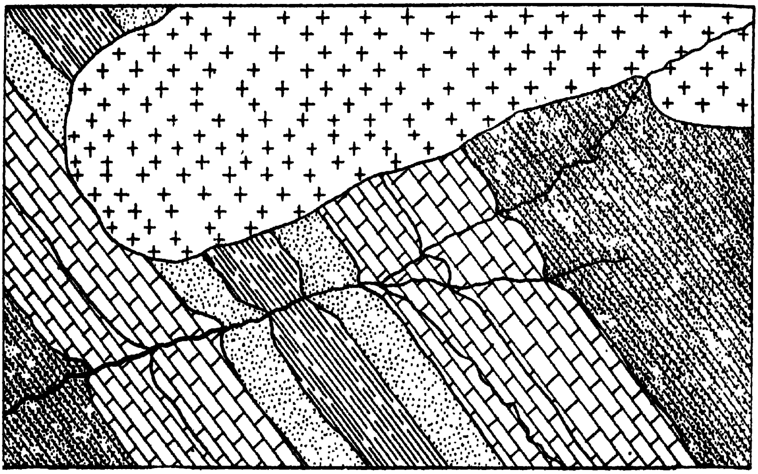


FIG. 14-19. Geologic map of inclined beds.

In symmetrical folds, the dip of the opposing limbs is the same; in asymmetrical folds, one limb dips more steeply than the other. If the dip determinations can be made, therefore, the symmetry can be found. If the topography is quite level, a marked variation in width of outcrop frequently indicates a change of dip, hence asymmetry of folding.

An aid in interpreting geologic maps is to turn the map so that the observer looks in the direction of plunge (down dip). In this position the plan map may be read directly as a cross section; anticlines, synclines, and stratigraphic succession thus become immediately apparent.

*Faults.* Well-established faults are shown on geologic maps by continuous lines. Broken lines of the same weight show where the fault is extrapolated or less securely established. The dip and strike of fault surfaces can be estimated by the methods already described, i.e., by a consideration of the deflection of the fault trace with respect

to valleys and hills. If the direction of dip can be determined from the map, the type of fault, normal or reverse, can be inferred. If the fault surface dips beneath the older of the adjacent beds, the fault is probably of the reverse type. If the fault surface dips beneath the younger beds, it is probably a normal fault.

If strata normally present in a rock sequence have been eliminated or duplicated by faulting, as shown on a geologic map, it is possible in some cases to estimate the fault displacement. If the involved beds are horizontal, the vertical displacement (throw) in a normal fault cannot be less than the thickness of eliminated beds, and the maximum throw would be the thickness of the eliminated beds plus nearly the thicknesses of the two formations brought into juxtaposition by the faulting. If the beds and fault were uniformly inclined, trigonometric solutions would be readily apparent. However, in many faulted areas the beds are disturbed, the attitude of the fault changes from place to place, and further, the amount of displacement in the direction of strike and up and down dip varies. On many maps, therefore, it is impossible to determine the amounts of displacements caused by faulting. Faults are seldom exposed continuously over long distances in the field. Too frequently the fault zone is topographically low, without bedrock exposures; hence the trace of the fault as shown on the map may be only approximately correct.

*Unconformities.* Unconformities can be recognized on geological maps by noting the succession and distribution of beds, by structural discordances, overlap, or truncation of dikes, faults or other structures.

If the unconformity is between essentially horizontal beds, two formations normally separated by other sediments are shown in contact. For example, if a Devonian formation overlies directly a Cambrian formation, unconformity is the probable explanation. The normal sequence of formations in the map area is shown in the map legend.

If the unconformity is angular, the difference in structure is readily apparent in the lithologic patterns on the map. The trans-

gression of a formation across other formation boundaries, i e, if several formations are crossed by a younger formation which conceals or covers them, unconformity is probable. In the same way, if a number of dikes are cut off at a formation boundary, it is probable that the formation truncating them is unconformable. Low-angle faults may give patterns similar to those of unconformity. As a result of faulting, older formations usually truncate younger rocks, whereas if the explanation is unconformity, younger beds truncate older rocks and structures.

***Geologic Sections.*** It is frequently necessary or desirable for engineering purposes to construct cross sections from a geological map to show the underground conditions along certain routes or lines. For choosing tunnel routes or dam sites, for mining excavation, and for many other purposes, geologic cross sections are indispensable. Because rock exposures are not everywhere found along the desired line of section, and because in areas of deformed rock the geologic map and sections constructed from it may be locally in error or subject to doubt, it is frequently necessary to check the

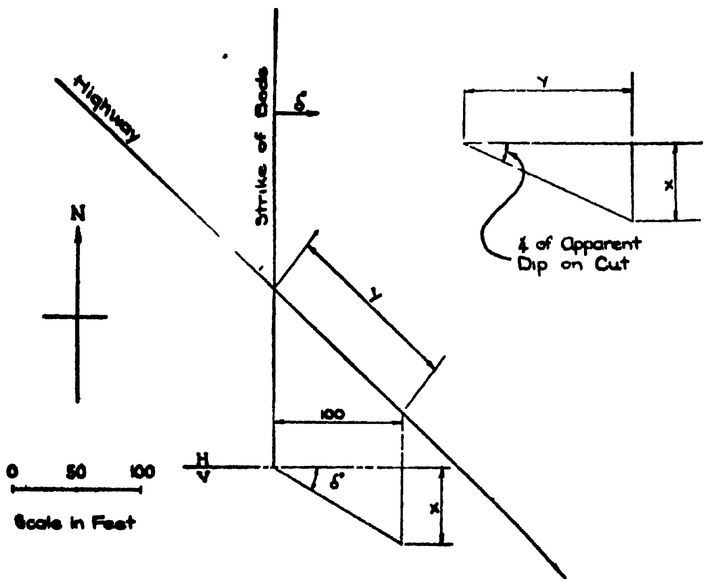



Fig. 14 20. Determination of apparent dip

inferences by drilling. Interpretation of the map and sections, however, minimizes the necessary exploration by drill and directs attention to those localities where boring will secure the most useful and most necessary supplementary information.

The construction of geologic cross sections normal to the strike of the rock has already been described and needs no elaboration. True dips can be plotted only on sections which are at right angles to the strike because, by definition, the dip of a geological structure is the measure of the maximum inclination of the structure and hence is in a direction normal to the strike. Oblique sections, however, are more frequently demanded than are normal cross sections, and the apparent dip of the structure in the direction of the oblique section must be established before it can be plotted. There are a number of solutions for this problem, familiar to students of descrip-

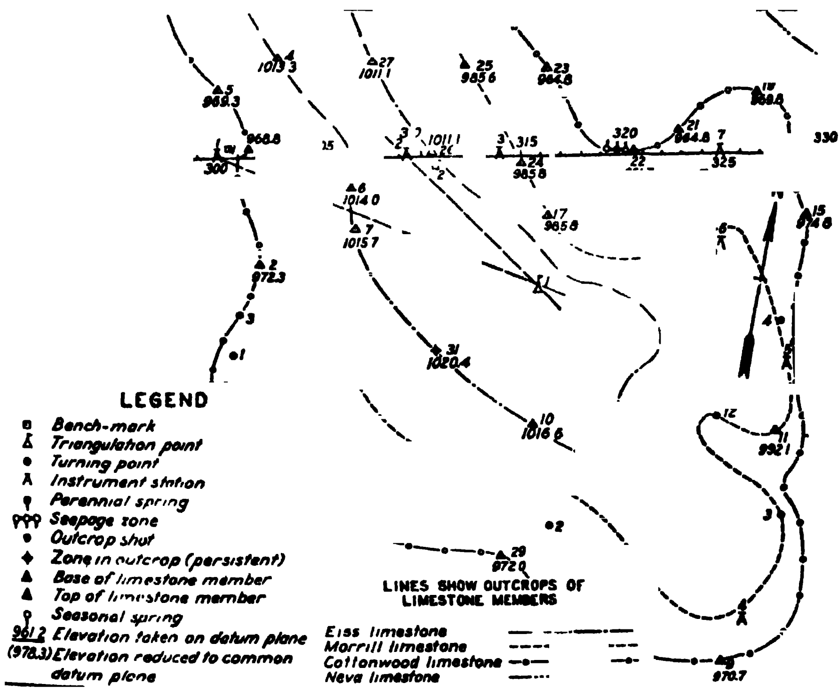



FIG. 14-21. Plane-table survey of exposures along highway route. (Courtesy of *Better Roads*)

tive geometry. One of the simplest and most direct solutions, however, is illustrated in the following example: A vertical-sided road cut is to be made in a N 45° W direction through beds which strike north and dip 35° easterly. What will be the slope (apparent dip) of the beds on the cut? Fig. 14-20 illustrates the solution. A cross section is drawn at right angles to the strike, showing the true dip of the beds. At a scaled distance of 100 feet (or any convenient distance) a strike line is drawn parallel to the strike of the beds. This is a structural contour, the depth value of which can be scaled from the diagram ($x$ in Fig. 14-20). Anywhere on the structural contour the bed is $x$ feet below the surface. From $a$ to $b$, therefore, along the line of the cut, the bed drops $x$ feet. The angle whose tangent is $\frac{x}{ab}$ consequently is the desired angle of slope. The problem is easily reversed, i.e., given the strike and the apparent dip in a certain direction, true dip is readily found.

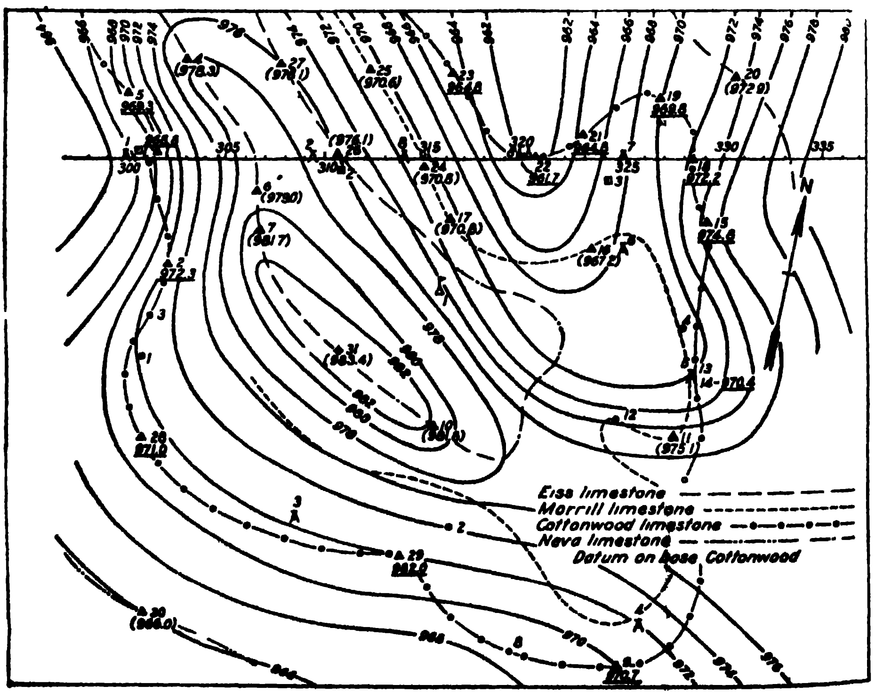



FIG. 14-22. Structural contour map of datum-plane stratum. (Courtesy of *Better Roads*)

***Example of Maps and Sections Used in Engineering Practice.*** The use of geologic maps and sections in engineering practice is well illustrated by the accompanying figures, which were prepared by the Kansas State Highway Commission as a part of a preliminary road survey (Figs 14-21, 14-22, 14-23, and 14-24) "First, a plane-table survey is made of the exposed outcrops (Fig. 14-21) The most desirable member of the outcropping formations is chosen as a datum or control plane Second, the plane table survey of the exposed outcrops is converted into a structural contour map of the stratum chosen as the datum plane (Fig 14-22) Third, from a compilation of the geologic sections of the sedimentary rocks in the locality of the survey, a profile is projected along the center line of the project, using the contour lines of the datum plane as control elevations (Fig 14-23) Sedimentary formations are generally found to be fairly uniform within the limits of any one project Sounding tools

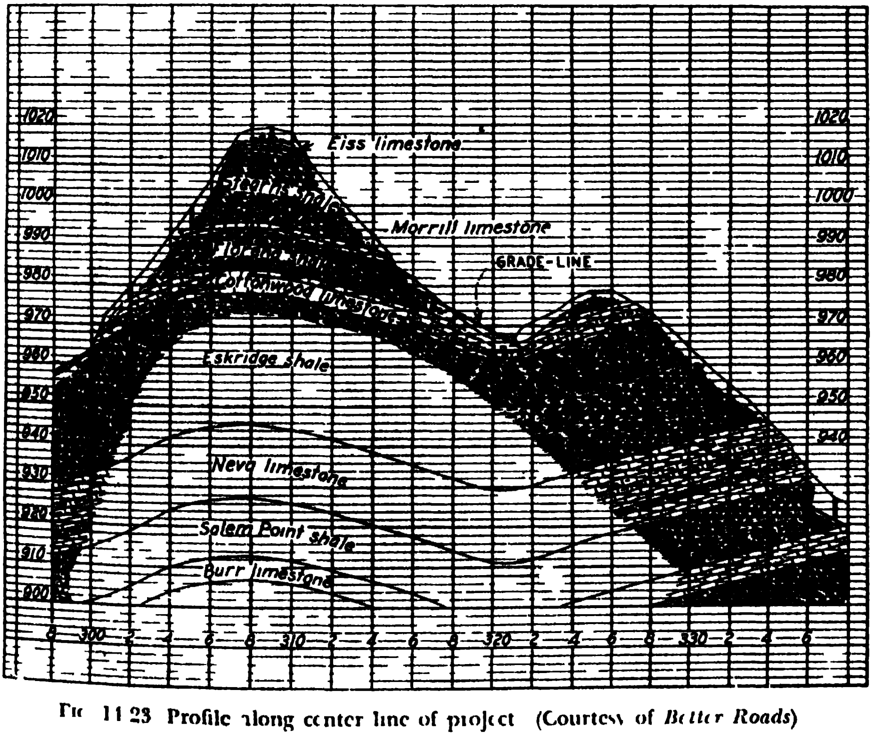



Fig. 14-23 Profile along center line of project (Courtesy of *Better Roads*)

are used to explore the mantle covering and check on the projection The resulting profile shows the underlying geology at each station along the centerline. The underlying geology is also shown at right

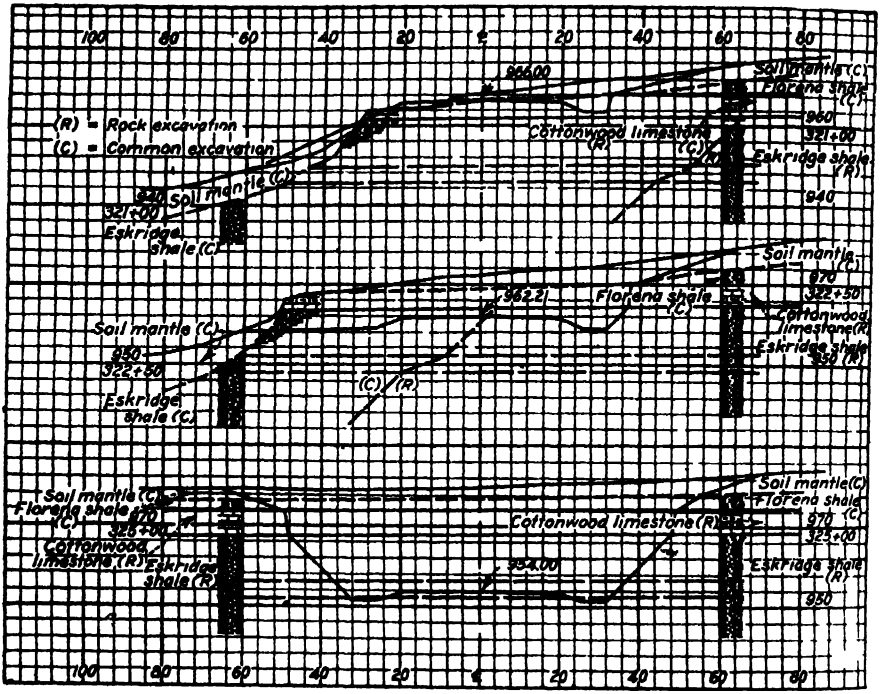



Fig 14 24 Cross section showing underlying geology (Courtesy of *Better Roads*)

angles to the profile on each cross section taken by the road survey party (Fig 14-24)." [1]

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ARTICLE

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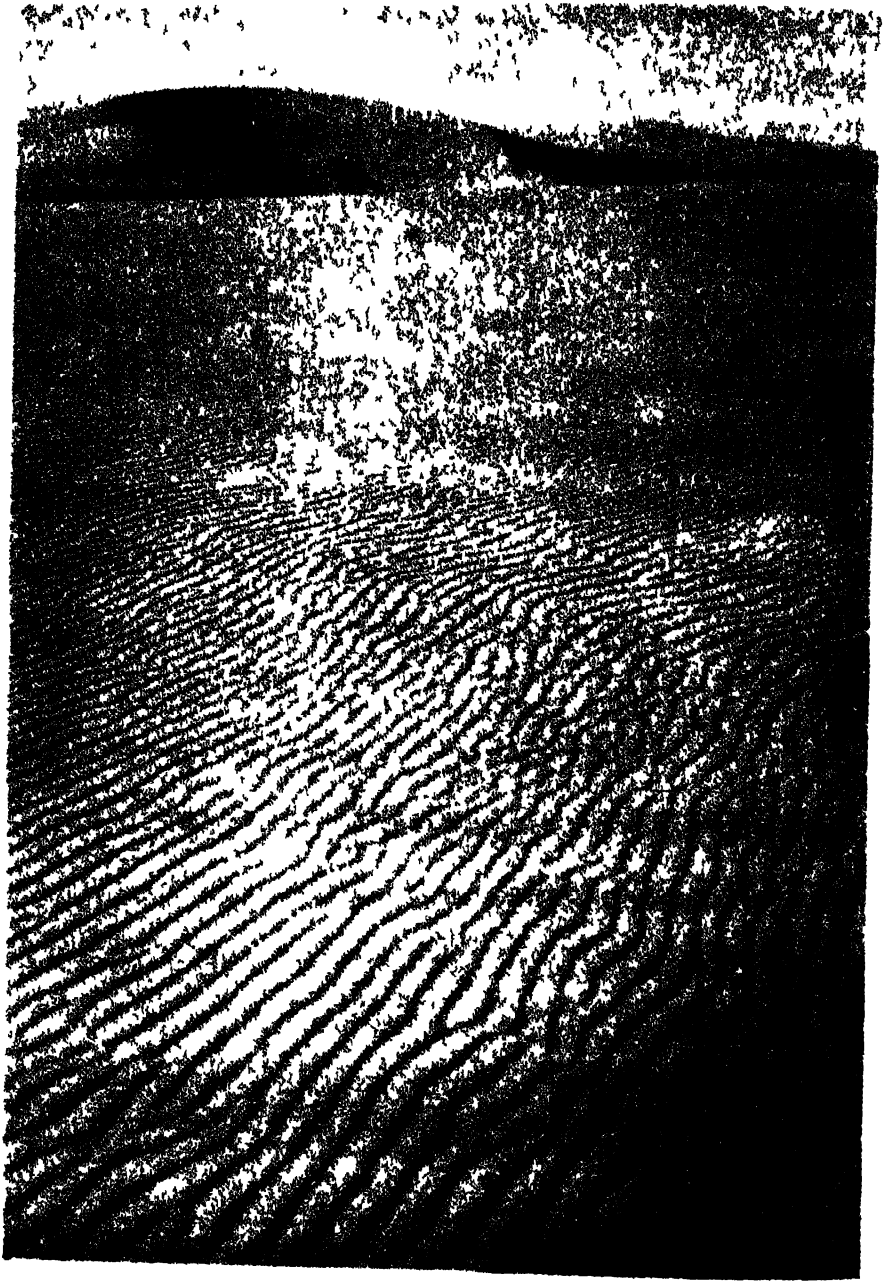


*The Texas Company*

WIND WORK IN AN ARID REGION BARCHANES AND WIND RIPPED SAND

## CHAPTER XV

# THE ATMOSPHERE

THE ATMOSPHERE IS A TURBULENT GASEOUS ENVELOPE THAT surrounds the solid earth. On the average each person breathes thirty to forty pounds of air per day. By its agency weather is produced and, like the poor, weather is always with us. Weather not only constitutes a topic of conversation, but is also of vital importance in the execution of many types of engineering project. Many a construction job has been delayed by adverse weather, and certain construction activity may be undertaken, advisedly, only at certain seasons or in favorable weather.

Engineering attention has been focused on winds by the failure of bridges under wind load and by the recent necessity of designing tall towers (radio towers up to 2000 feet tall). With these tall structures wind loads must be carried by guys and stiffening members supported by adequate foundations.

*Climate,* the total of weather averages over a long period, is a fundamental influence on engineering practice and design. The mention of *frost* to a mid-latitude engineer may well connote *heave,* and correlated problems come at once to mind. Diurnal and season ranges of temperature govern expansion-contraction allowances according to the structural materials employed. The extremes that must be anticipated are of higher concern than the means.

### THE WEATHER ELEMENTS

Weather is the summation of local atmospheric conditions at any particular time. Weather varies from time to time and from

place to place on the face of the earth, and the primary elements of variation—the weather elements—are temperature, winds and air pressure, humidity, and precipitation.

***Temperature.*** The sun is the only important source of heat for the earth's surface. Insolation, energy received from the sun, varies with the angle of incidence of the rays and the duration of sunshine during the 24-hour period. If there were no disturbing factors, the gradation of temperature would be uniform from the equator to the poles; stated differently, the temperature would be uniform along any parallel of latitude. That this is not true is well illustrated by comparing the mild temperatures of the British Isles between latitudes 50° and 55° with those of the bleak coasts of Newfoundland and Labrador in the same latitudes.

The atmosphere is warmed by the heat returned to it from the earth; little is absorbed directly from solar radiation. Land areas both absorb and radiate heat more rapidly than do water bodies. Hence, the lands heat more quickly and to higher temperatures and cool more rapidly and to lower temperatures than do adjacent waters. The air covering the two types of surface shares the effect of the contrasting specific heats of land and water. Air, however, is more or less constantly in motion, and the modifying effects of seas and lands are carried leeward. Land areas to the leeward of large seas or lakes (e.g. the British Isles) thus have a more equable distribution of temperature than do lands not so situated (e.g. Labrador). The extremes of temperature experienced in the interiors of large land masses are similarly explained. The invasion of middle latitudes by huge tropical and polar air masses also greatly modifies the temperatures of the invaded regions. These air mass movements are discussed in the sections dealing with storms and with weather maps.

The highest temperatures of the day are ordinarily observed in mid-afternoon rather than at noon when the sun is highest. The explanation of this temperature lag is that heat input (insolation) although at a maximum at noon, exceeds heat loss (radiation) until mid-afternoon. The earth, consequently, is still heating after the period of highest sun. An analogous explanation holds for the an

nual distribution of temperature; the extremes commonly follow the solstices rather than coinciding with them.

Vertical gradients of temperature are as familiar as horizontal gradients. The air near the earth's surface not only receives more heat by earth radiation than the upper air, but also absorbs more, because it is denser, dirtier, and more moist than the upper air. Air temperatures, therefore, are ordinarily higher near the surface than above. The *normal* vertical gradient is about 3½° F. per thousand feet. Because rising air expands with the reduction of pressure, it cools. Conversely, sinking air, compressed, warms. If through heat loss the ground becomes colder than the overlying air, a stable, colder, and denser air layer beneath a warmer upper layer may form. The condition, called *temperature inversion*, is favored by the long, calm and clear nights of winter. The tempering effects of altitude are strikingly shown by the live glaciers of high mountains within the tropics. The elevated plateau of central Mexico, which has a delightfully temperate climate altogether in contrast with the steaming climates of adjacent lowlands, gives another example of the effect of altitude.

Because cold air is denser and heavier than warm air, it tends to settle into valleys and depressions. Trewartha[1] records, "On one occasion, during a cold spell, a temperature of −8.9 was registered on top of Mount Washington, N. H., while records of −23 to −31° were recorded in the surrounding lowlands." The downslope movement of cold air is called *air drainage*. Because of air drainage, lowlands rather than uplands are subject to the earliest frosts of autumn and the latest frosts of spring. A cloudy or humid atmosphere serves to blanket the earth, reducing radiation. Frosts are much more likely, therefore, when the skies are cloudless than when cloudy. In deserts, where clouds seldom inhibit radiation, day temperatures of over 100° may change to night temperatures below freezing.

The American Gas Association has developed a system of regional and local temperature evaluation that is useful in a variety of engi-

[1] Trewartha, G. T., *An Introduction to Climate*, 1954.

neering applications. The basis of this system is the fact most people find it desirable to heat a building when the average daily temperature drops below 65° F. for any length of time; therefore, 65° F. is the base temperature in figuring degree-days. *Degree-days* are the number of degrees that the mean temperature for a 24-hour day differs from 65° F. The mean temperature of a day is the average of the highest and the lowest reading for the 24 hours. Thus: the highest temperature recorded for September 30 might be 75°, the lowest 33°F. The mean temperature would be 54° or 11 degree-days ($65 - 54 = 11$). Inasmuch as each building uses an approximately constant amount of energy for heating or cooling per degree-day, the system gives a basis of comparison for fuel consumption studies For example: during a certain period, a plant consumes an extraordinary amount of fuel; the degree to which the unusual consumption is related to outside temperatures will be shown by degree-day analysis. The use of the system also permits rational design of heating and cooling units. The normal annual degree-day differences within the United States are shown in Fig. 15-1, and degree-day data are compiled for monthly release by the United States Weather Bureau. Monthly "normal" degree-day maps serve as guides for regional fuel requirements and for the allotment of shipments and storage. Other services and distributions dependent on temperature, also, may be rationally planned by reference to the degree-day system.

***Air Pressure and Winds.*** A wind is an essentially horizontal air current, the direction and velocity of which are basically determined by differences in air pressure. There is thus a fundamental relation between winds and the distribution of surface temperatures. Where the earth's surface is highly heated, the air warmed by radiation becomes less dense and rises. The area is one of low barometric pressure. Conversely, if air is cooled at the surface, it becomes denser; barometric pressure rises, and air settles downward. The seasonally reversed winds of eastern Asia, called *monsoons*, well exemplify these effects. During the winter months the land mass cools and a great high-pressure area of cold settling air develops, with

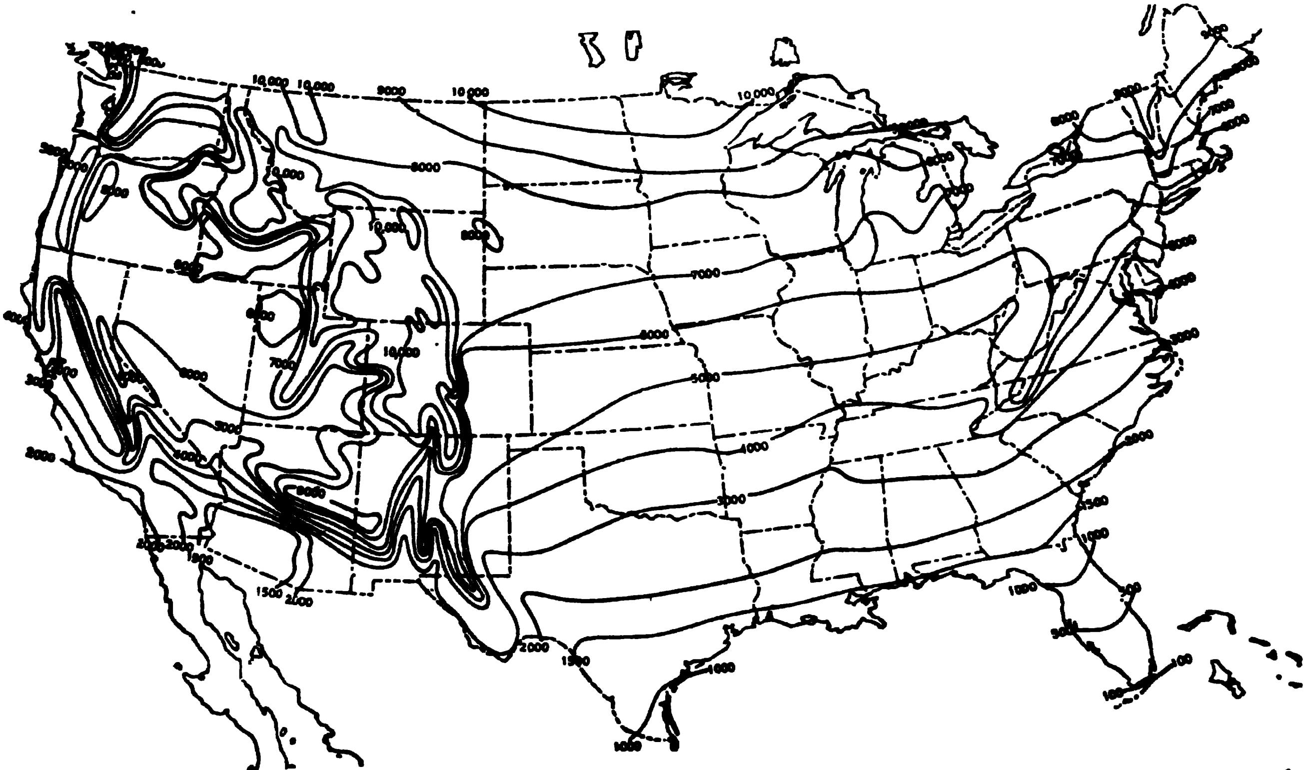


Fig. 15-1. Degree-day map of the United States. (U. S. Weather Bureau) The map shows the average annual number of degree-days over the United States. The heavy lines connect points having approximately the same average number of degree-days each year. For example, every point through which the 5000 line passes has an average annual degree-day total of about 5000. The complex pattern in western states is due to the influence of the mountains.

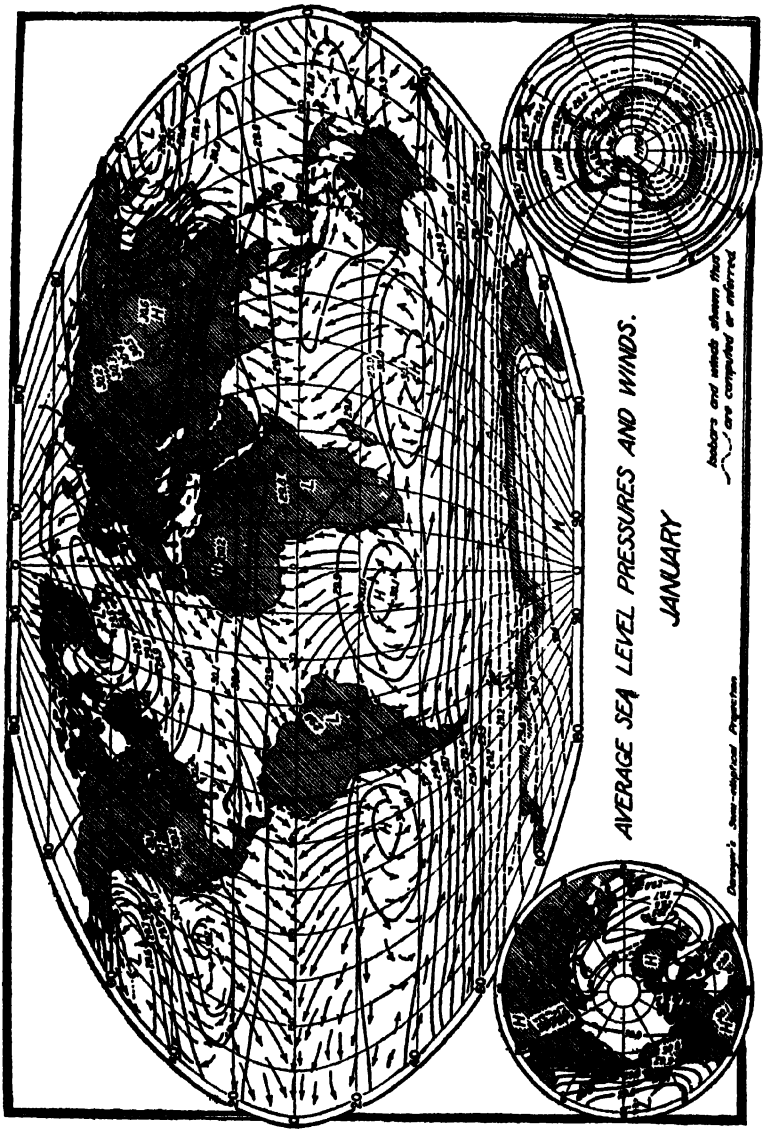



FIG. 15-2 From Trewartha, *An Introduction to Weather and Climate*, reproduced by courtesy of McGraw Hill Book Company, Inc.

its center over the Gobi Desert. From this high-pressure center, air flows outward—the winter monsoon. During the summer months, conditions are reversed: low barometric pressure with light and rising air replaces the winter high. Cooler air from the ocean moves in to replace air forced upward. The indraft is the summer monsoon.

*Planetary Winds.* On an earth-wide scale, a system of prevailing winds called the planetary wind system can be distinguished, as illustrated by the map of Fig. 15-2. The principal controls of the planetary winds are the distribution of barometric pressure and the

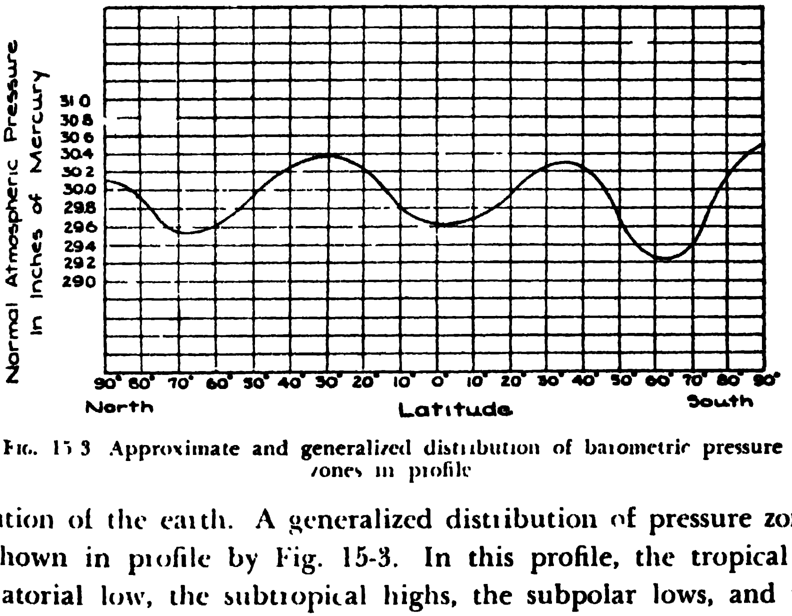
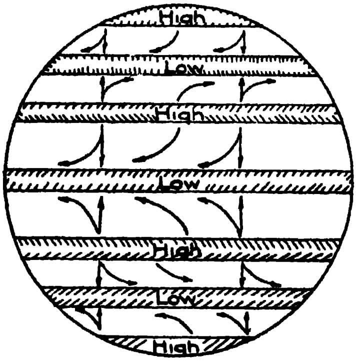



FIG. 15-3 Approximate and generalized distribution of barometric pressure zones in profile

rotation of the earth. A generalized distribution of pressure zones is shown in profile by Fig. 15-3. In this profile, the tropical or equatorial low, the subtropical highs, the subpolar lows, and the polar highs give shape to the curve. If the winds were not deflected by earth rotation, the major currents would flow poleward and equatorward (north and south) from the highs to the lows. The movements would be as indicated by the straight arrows in Fig. 15-4. Moving bodies, however, are subject to *Ferrel's law,* which states that in the Northern Hemisphere moving bodies are deflected to the right (clockwise) and that in the Southern Hemisphere moving bodies are deflected to the left (counterclockwise). (To visualize the

sense of *right* and *left* deflection, face in the same direction that the body moves.) The curved arrows of Fig. 15-4 show the idealized planetary wind system, as affected by earth rotation. It will be noted that the winds blowing equatorward from the subtropical highs are deflected into northeast and southeast winds (winds are named by




| | |
|---|---|
| Polar Highs | 90°-80° |
| Subpolar Lows | 55°-65° |
| Subtropical Highs | 30°-40° |
| Equatorial Low | 5°-5° |

FIG. 15 4 Diagrammatic representation of the planetary wind system as related to the barometric pressure zones

the direction *from* which they blow) called trade winds. The winds blowing poleward from the subtropical highs are deflected into westerlies, and the winds moving equatorward from the polar highs are deflected into easterlies.

The explanation of the pressure belts involves both insolation and earth rotation. The equatorial low is the zone of maximum heat reception. The air currents are predominantly upward, and the belt is one of calms, the *doldrums*. As the equatorial air rises, it spreads out, moving poleward. Deflected in accordance with Ferrel's law, a barrier is piled up against poleward movement. This barrier is passed by a part of the poleward-moving air, but some of it, relatively cool and dense, settles, forming the subequatorial highs. In the settling zone, surface currents are light and variable, the *horse latitudes*. The subpolar lows appear to be either the result of a centrifugal lift caused by air spiraling towards the poles or by the forcing aloft of air warmed by the release of latent heat at the junction of westerlies and polar easterlies. The polar highs are the result of low surface temperatures over Greenland, the Arctic Ocean, and Antarctica.

The inclination of the earth's axis causes the annual shift of vertical sun rays between $23\frac{1}{2}°$ north latitude and $23\frac{1}{2}°$ south latitude; hence, the heat equator, the pressure belts, and the wind belts shift seasonally. For this reason, an area of the northern hemisphere that is in the southerly margin of the west-wind belt in the wintertime may be in the trade-wind belt when the sun makes its apparent journey northward in the summer. Over the seas, the latitudinal shifts of the wind belts is on the order of 10°; on the continents, although not so clearly marked, it may be considerably more.

There are many reasons why the diagrammatic planetary wind system shown in Fig. 15-4 falls short of reality. The distribution of lands and seas with their differential heating and cooling, the presence of mountain barriers and oceanic currents, and the phenomena of storms all cause departures from the idealized scheme. In spite of departure from perfection, the planetary wind system is well developed as shown in the map of prevailing winds (Fig. 15-2).

*Local Winds.* Regional departures from the planetary wind system—the monsoons—have already been mentioned for eastern Asia. The subcontinent of India, also, has a strongly developed monsoonal system, independent of that of eastern Asia; and other continents—notably Australia and North America—have similar though less pronounced monsoonal regimes.

Similar in cause to the monsoons are the land and sea breezes prevalent along many shorelines. During the day, land may become enough warmer than adjacent water that in the afternoon a sea breeze may set in which blows on shore until early evening. The sea breeze seldom penetrates inland more than 10 miles, and ordinarily its effect is felt over a narrower coastal zone. During the night the land cools more than the adjacent water so that an outblowing land breeze may develop, which commonly begins sometime after midnight and usually persists until the early morning hours. Mountain and valley breezes, like the land and sea breezes, are diurnal results of differential heating and cooling of adjacent areas. Mountain slopes, inclined so that they are more nearly perpendicular to

the sun's rays than adjacent flat lands, heat during the day to higher temperatures. Updrafts of warm air ascend the slopes, often giving rise to late-afternoon mountain showers. In the evening, mountain slopes lose heat more rapidly by radiation than do the adjacent lowlands, and cool breezes move downslope. Air drainage tends to follow the valleys, and the cool breezes are, therefore, concentrated in the valleys.

Another type of local wind is associated with mountain and plain. If a low-pressure area (cyclone) draws air over a mountain barrier, it frequently descends the leeward slopes as a relatively warm, dry wind called a *foehn* or *chinook*. The warmth gained by compression during the descent may be supplemented by latent heat released during condensation induced by the ascent of the windward slopes. Chinook winds are most frequent in the winter months Along the eastern base of the Rocky Mountains from Colorado to northern Canada, the chinook is a common occurrence. In these regions an overnight rise of temperature due to the chinook often amounts to 40° or 50°.

Local changes in wind direction and velocity are associated with storms. Especially is this true in the prevailing-westerly wind belts of the middle latitudes Because storms account for much of the variability of weather in the westerly wind belts and are of importance, also, in other regions, they are treated separately in a subsequent section of this chapter.

***Humidity and Condensation.*** *Humidity,* used as a weather term, refers to water vapor in the air. If the water vapor is condensed, a variety of physical states result Of these, *rain, hail,* and *snow* fall more or less rapidly through the air and hence are forms of precipitation. The other forms of atmospheric condensation are *clouds, fog, dew,* and *frost.* Both water vapor and its condensation types are weather elements of first-rank importance.

*Humidity. Relative humidity* expresses the percentage of moisture saturation of the air. The percentage of saturation varies with temperature. For example: a cubic foot of air at 0° F. can hold a thousandth of an ounce of water vapor; the relative humidity is

100 per cent. At a temperature of 80° F., a cubic foot of air can hold an absolute amount of twenty-two hundredths of an ounce of water vapor. With that amount, it is 100 per cent saturated. If at the same temperature (80° F.) an absolute amount of eleven hundredths of an ounce of water vapor is present, the relative humidity is 50 per cent. From the illustrations given, it can be seen that relative humidity drops with a rise in temperature; correspondingly, relative humidity rises with a drop in temperature. Condensation takes place when the temperature drops to the degree at which relative humidity rises to 100 per cent. That temperature is called the *dew point;* it varies according to the absolute amount of water vapor present.

Relative humidity affects human comfort and efficiency. Together with air circulation, it determines the sensible or effective temperatures. If relative humidity is low, evaporation, a heat absorbing process, readily takes place; if relative humidity is high, evaporation is inhibited. Thus, the effective or felt temperatures vary with the relative humidity. Wet and dry bulb thermometer readings can be translated into effective temperature degrees by means of the chart shown in Fig. 15-5. The point of intersection of a straight line between the wet and dry bulb readings and the proper effective temperature curve gives the effective temperature. The effective temperature curves vary for different people, and they differ for one individual according to activity. The curves presented are probably valid for many people moderately active indoors. Engineers engaged in the operation of deep mines or construction in rigorous climates, for example desert, jungle, or polar regions, can make use of effective temperature determinations in caring for the welfare of their people and in gauging the productivity of labor or the progress of work. Efficient and therefore economical operation of industrial air-conditioning units is geared to effective temperature. It is stated that in Washington, D. C., many government offices are closed when the effective temperature reaches 84°.

*Condensation.* The change from water vapor to liquid or solid form is called *condensation.* As already explained, condensation

about hygroscopic particles in air suspension takes place when the temperature drops to the dew point at which relative humidity is 100 per cent. If the temperature of condensation is below freezing, water vapor, without going through a liquid state, crystallizes di-

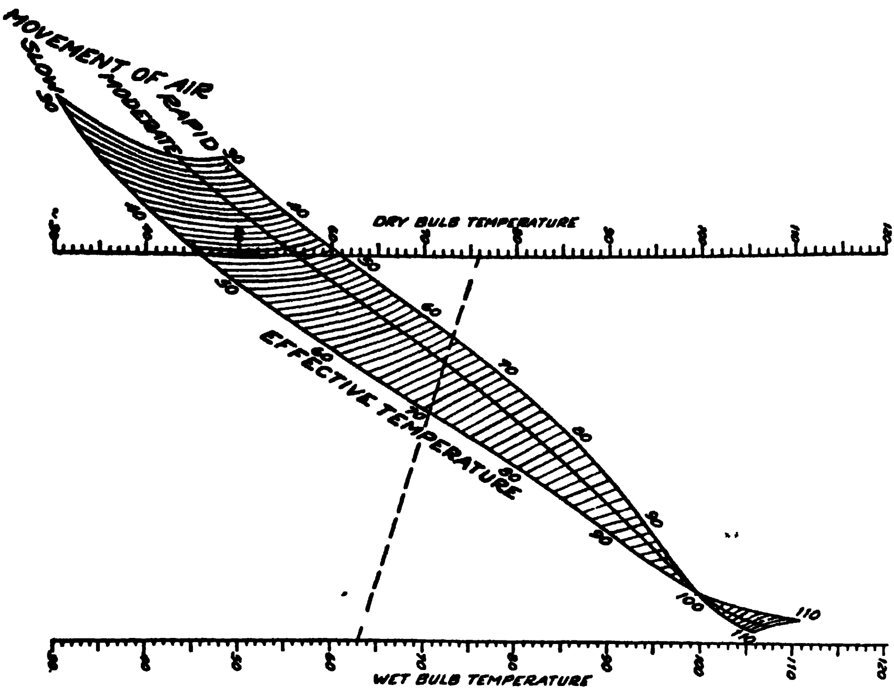



FIG. 15-5. Effective temperature chart (U S Weather Bureau)

rectly into frost or snow. Condensation at or near the ground level forms frost, dew, and fog. Condensation aloft forms clouds and precipitation. The principal source of atmospheric water vapor is the seas. Winds distribute the water vapor, and condensation returns it to the surface of the earth. Much of the part that falls on land is eventually returned to the seas. This circulation of water, the hydrologic cycle, is illustrated by Fig. 16-1.

*Dew and Frost.* Dew is condensed water vapor in liquid form, adhering to the surfaces on which it condensed. Frost is condensed water vapor in the form of ice crystals adhering to the surfaces on

which the sublimation took place. (The engineer will note that *frost* is also used in a somewhat different sense, referring to frozen soil moisture.) If the temperature of condensation is below freezing, frost forms. The surfaces on which condensation takes place are cooled by radiation; consequently, any inhibition of radiation tends to prevent condensation. Active air circulation rapidly distributes the air which comes in contact with cool surfaces and also tends to prevent condensation. Cool nights when the air is both clear and calm, therefore, are favorable for the formation of frost or dew.

*Fogs and Clouds.* Fogs and clouds are composed of condensed water vapor in particles small enough to remain in suspension.

Fog dissipation measures for airfields are still in the experimental stages. To reduce relative humidity, both heating measures and hygroscopic sprays have been tried. Civil airfields have not yet adopted either method.

Clouds are formed principally by adiabatic cooling of rising air. Air expands as it rises because less weight is acting to compress it. Expansion without heat addition lowers the temperature—hence, clouds. Clouds are also formed to a limited extent by mixing air currents.

Fortunately, cloud classification has been standardized, and the International System is used by meteorologists the world over. Standard symbols representing the cloud types are also internationally used. The following classification (International System) and abbreviated definitions are taken from a weather map published by the United States Weather Bureau.

## INTERNATIONAL CLOUD CLASSIFICATION

In the International System there are ten principal kinds of clouds. Their names, classification and mean heights are shown in the following table. The mean heights are for temperate latitudes and refer not to sea level but to the general level of land in the region. There is nearly always some variation from the mean height, and in certain cases there may be large departures. Thus, cirrus clouds may sometimes be observed as low as 10,000 feet in temperate regions and at lower levels in higher latitudes.

FAMILY A: HIGH CLOUDS

(Mean lower level, 20,000 feet)

1. Cirrus
2. Cirrocumulus
3. Cirrostratus

FAMILY B: MIDDLE CLOUDS

(Mean upper level 20,000 feet; mean lower level, 6500 feet)

4. Altocumulus
5. Altostratus

FAMILY C: LOW CLOUDS

(Mean upper level 6500 feet, mean lower level, close to surface)

6. Stratocumulus
7. Stratus
8. Nimbostratus

FAMILY D: CLOUDS WITH VERTICAL DEVELOPMENT

(Mean upper level, that of cirrus, mean lower level, 1600 feet)

9. Cumulus
10. Cumulonimbus

All precipitation comes from clouds; and although cooling of moisture-bearing air explains all precipitation, it is convenient to recognize four rainfall types: convectional, orogenic, monsoonal, and cyclonic.

*Convectional Rain.* Convectional rains are those caused by the expansion and cooling of rising convectional air currents. By mid or late afternoon in the doldrum belt, radiation from the heated surfaces gives rise to convectional updrafts of humid air. The expansion and cooling of these upcurrents result in the convectional showers of the humid tropics that take place with almost clock-like regularity nearly every afternoon. Convectional rains are sun generated and controlled. They are "high sun" rains In the summer months of the mid-latitudes, the common late afternoon or evening

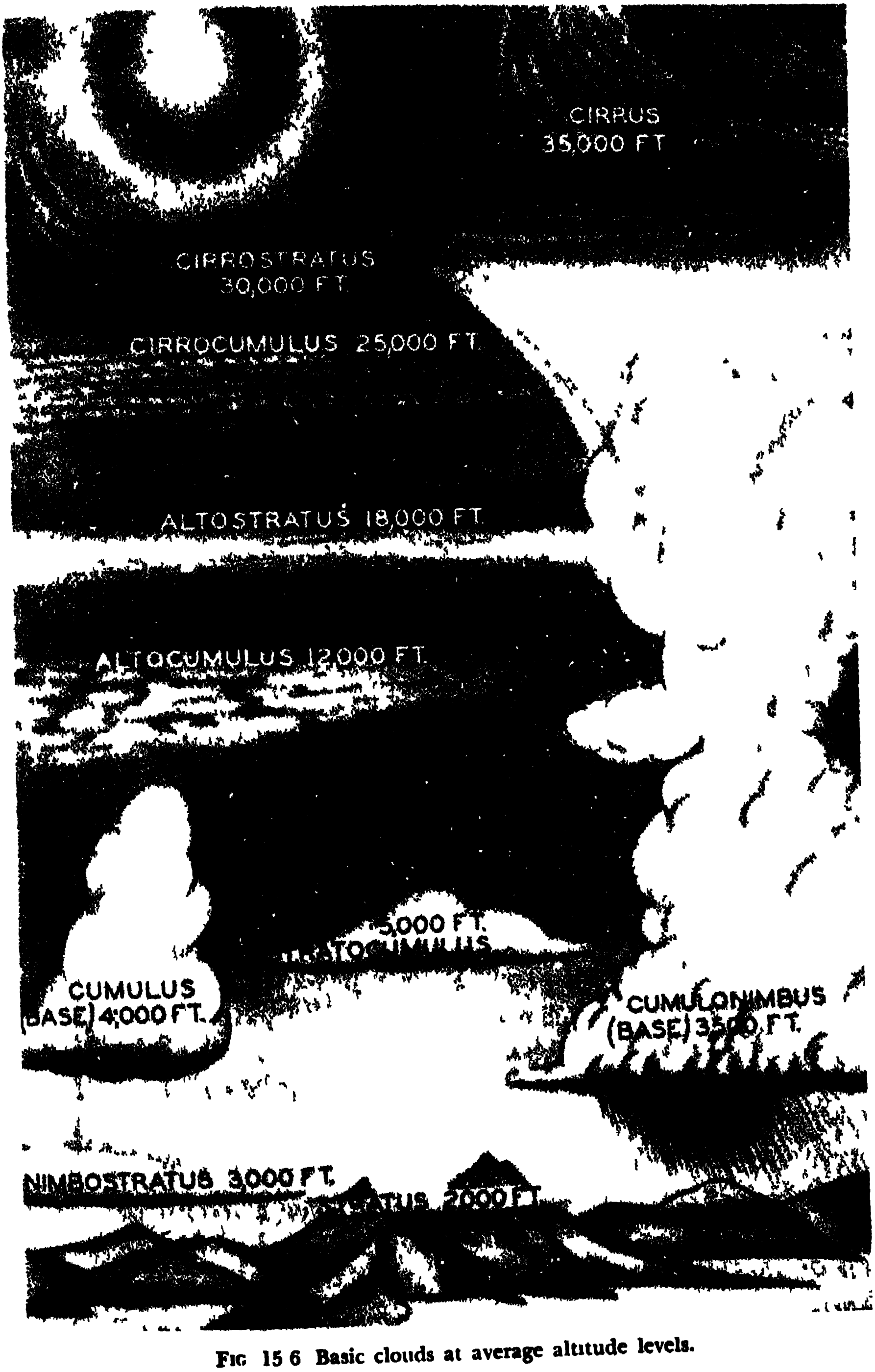



FIG 15 6 Basic clouds at average altitude levels.

showers are convectional. In the hot spells convectional turbulence often generates thunder and lightning which accompany the shower.

*Orogenic Rain.* Where mountain barriers lie athwart the prevailing winds, moist air is forced aloft, and orogenic rains result from the cooling. Orogenic rain is most abundant where the wind has had a long passage over water and thus has been afforded opportunity to gather moisture. Mountainous windward coasts, therefore, are sites of especially heavy orogenic rains. Leeward of the mountains, semiarid conditions are common because not only is the relative humidity of the air decreased by the compressional warming of its descent, but also its absolute humidity is decreased by the amount of moisture precipitated on the windward slopes. The northwestern coast of the United States, where the Cascade and Olympic mountains rise precipitously across the path of the prevailing westerlies, gives an excellent example of a well-drenched windward coast succeeded inland by a moisture-deficient leeward "rain shadow" zone. Similar orogenic rains fall in the trade-wind belt. It may be remarked, however, that the trade winds, except where they impinge on elevated coasts, are drying winds because their trend is from cooler to warmer latitudes; they are headed from the subtropical highs towards the equatorial low-pressure belt. Within the trade-wind zones, therefore, drought is prevalent The trade-wind belt is the principal desert belt; the Arabian and Sahara, the Atacama, and the Kalihari are examples. The windward shores of elevated land masses, island or continent, within the trade-wind zones, however, are well watered.

*Monsoonal Rain.* The seasonal winds of eastern Asia have been explained as a result of the difference in specific heats of water and land. During the summer months, when the monsoon is blowing from sea to land, moisture-bearing air is brought inland; cooled by ascent, it gives rise to monsoonal rains. Where monsoonal winds meet mountainous terrain before they have lost their moisture, as for example in Burma and northeast India, some of the heaviest rainfalls on earth are recorded. At Akyab, Burma, the average annual rainfall is some 203 inches.

*Cyclonic Rain.* Cyclones are huge warm air masses of low pressure which travel irregularly from west to east in the west-wind belts. Because cyclones are made up of warm and rising air, they often bring rain. Much of the precipitation on the United States is associated with cyclones. Cyclonic rain is discussed in the following section on storms.

## Air Masses and Storms

The idealized planetary wind system is modified by the movements of huge air masses. In the belts of the prevailing westerlies, the movements of warm, low-pressure air masses and cold, high-pressure air masses are of prime climatic significance. The volume of air of these air masses is enormous; in many, the weight of air moved may be on the order of a hundred billion tons. Air masses develop where air movement is light, giving opportunity for the air to take on temperature characteristics of the area. The polar regions and the warm subtropical regions margining the trade winds are the principal sources of air masses. The air masses are named, according to their source, as *Polar* or *Tropical* and qualified according to whether they formed over continent or sea: as, continental Polar (cP) or maritime Tropical (mT). After they have formed, the air masses eventually move as giant density flows; the tropical air masses move poleward, the polar masses move southward, and both become somewhat modified as they travel. In common with other types of density flows, the air masses involved maintain their individuality and character to a surprising degree. Where one air mass meets another of differing character there is slight mixing; the temperatures and pressures change rather abruptly at the junction producing a *discontinuity* along quite definite fronts. Frontal zones, or *fronts,* consequently are the locus of weather changes. The position of the principal air-mass fronts, both tropical and polar, is variable in position. In the North American winter, the polar front frequently reaches the Gulf of Mexico; in summer its average position lies somewhat south of Hudson Bay.

***Storms.*** Almost any short sequence of the United States Weather

Bureau's *Daily Weather Map* shows barometric lows and highs. The areas inclosed by isobars (lines of equal barometric pressure) are commonly oval or elongate. The barometric lows are called cyclones; the highs are called anticyclones. In addition to the cyclones, storms of local intensity are significant. Examples are the tornado, hurricane, and thunder storm.

*Cyclones.* Although the term *cyclone* is popularly associated with winds of violence, actually the expression refers only to a moving low-pressure air mass of huge proportions. The passage of a cyclone in middle latitudes is usually to be noted by the cloudy or rainy weather, rise in temperature, and wind shifts associated.

The cyclonic storm consists of two fronts, an advance warm front and a rear cold front. Usually, the warm front overrides the cold air it overtakes as shown in Fig. 15-7. The warm front aloft thus passes

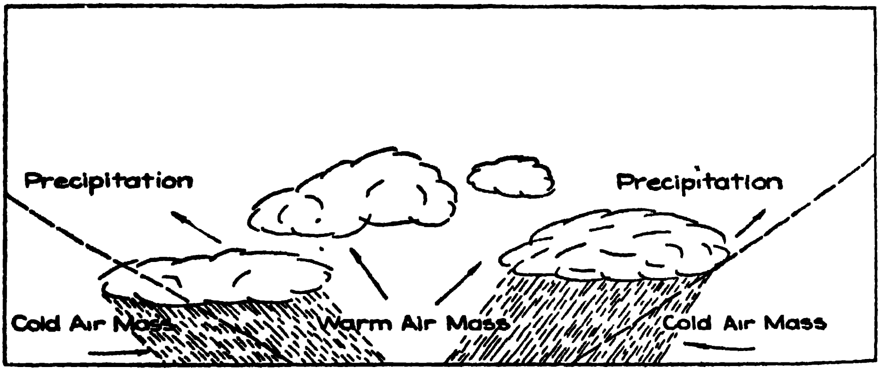



FIG. 15-7. Precipitation in association with warm and cold air masses.

over a surface point before it reaches the point at ground level. As the warm front advances, skies become cloudy, and often rain falls steadily, sometimes for hours. With the passage of the warm front and the approach of the center of the cyclone, broken clouds and even blue sky may appear. The following cold front is often marked by the bank of clouds clearly approaching along a definite line. Frequently, as shown in Fig. 15-7, the cold air thrusts under the warm air it is overtaking, and forces the warm air aloft where condensation, often with precipitation, follows. Because the cold front

is a more narrowly defined zone of discontinuity, it was called the "wind shift" or "squall line" long before fronts were known or recognized. Anticyclones are similarly explained as interaction of air masses along the polar front. Bulges of polar air or detached polar air masses (highs) make the anticyclones.

Although both the direction and rate of travel are irregular, the cyclones and anticyclones of the mid-latitudes move in general from west to east. These storm types are more strongly defined and travel more rapidly in winter than in summer. In summer, the average progress is between 400 and 500 miles per day; in winter, between 600 and 700 miles per day. It is because of the general west to east progress of storms in the mid-latitudes that the weather conditions of areas to the west of a place are of more significance in weather prediction than are the weather conditions to the east.

*Tornadoes.* Tornadoes, often called "twisters," are the most violently destructive storms known. These storms are of small size, with an average diameter of 1000 to 1500 feet. The average length of path tornadoes travel is between 10 and 40 miles; a few, however, are known to have traveled as far as 300 miles. Tornadoes advance at an average rate of 25 to 40 miles per hour, but the horizontal air velocity within the storm may be as much as 500 miles per hour. The central and southern plains states, just east of the Rocky Mountains, are the areas where tornadoes are most frequent. Tornadoes are most common between the hours of three and six o'clock in the afternoons of spring and early summer. Characteristically, a funnel-shaped cloud marks the center of the disturbance; rain and hail are frequent accompaniments. The origin of tornadoes is obscure. They are related to the squall lines of V shaped lows.

*Hurricanes.* Hurricanes, sometimes called *tropical cyclones* or *typhoons,* are small intense lows of tropical origin. The hurricane is essentially a large whirlwind of high velocity. Commonly, the diameter is on the order of 50 miles. The diameter of the area of hurricane-force winds, however, exceptionally may be as great as 250 miles.

Hurricanes that affect the United States originate in the West

Indies and advance northward at an average rate of 10 to 25 miles per hour, commonly along a parabolic path which carries them offshore up the Atlantic Seaboard (see Fig. 15-8). Frequently, however,

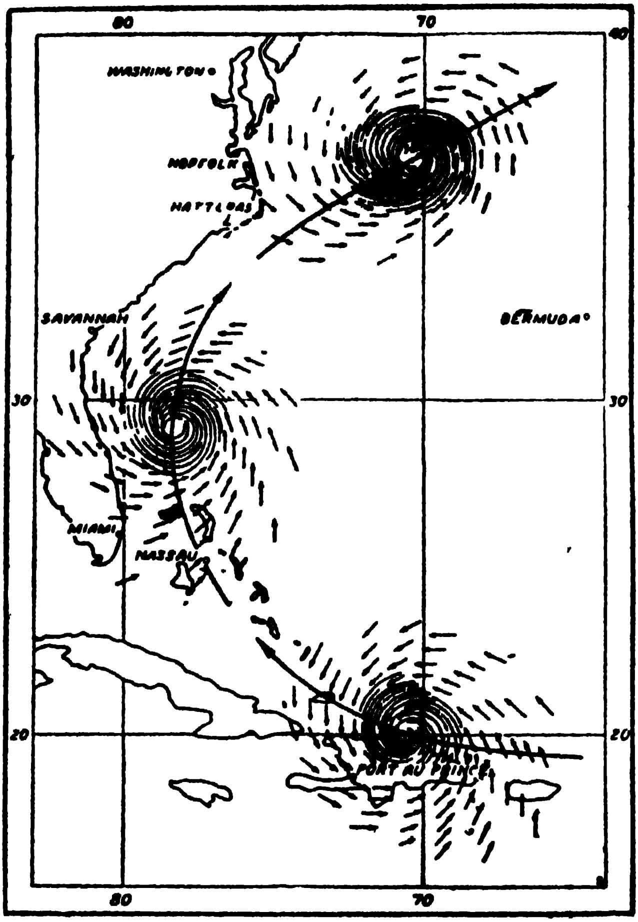



FIG. 15-8. Common path of tropical hurricanes up the Atlantic seaboard (U. S. Weather Bureau)

they reach the Gulf or Atlantic coastal areas, where wind-generated waves and associated heavy rainfall often cause more damage than the hurricane winds themselves. In the five-year period 1941-1945, hurricane property damage is estimated by the U. S. Weather Bureau

at a total of $296,924,100 for the United States, with loss of life placed at 107.

*Thunderstorms.* Thunderstorms are local disturbances caused by vigorous ascent of warm moist air. The violence of the updraft is often attested by the writhing clouds associated. High surface temperatures that result in convectional instability are a cause of thunderstorms. Entrapment or shoving aloft of warm moist air along an advancing cold front also are causes. The disruption of falling raindrops builds up electrical charges in different parts of the associated clouds, the discharge of which is lightning. Thunder is the result of the violent expansion of air caused by passage of the hot electrical current through it. Typically, heat thundershowers are late-afternoon, summer storms. The frontal thundershowers may occur at any season, but are more common in the warm months. They may arrive at any hour of the day. The release of latent heat of condensation maintains the storms.

## Geologic Work of Wind

Wind is simply air with a horizontal component of motion. The velocity of wind currents varies from nothing in an absolute calm to as much as 272 miles per hour, the maximum recorded velocity (Mt. Washington, N. H.). The vertical velocity gradient is generally steep. The lowest wind velocities are close to the ground because of the retarding effect of surface irregularities, brush, trees, and other obstructions. Because the lowest velocities are close to the ground, the wind is at a disadvantage in acquiring a sediment load. Tending to offset this, however, is the irregularity of currents near the ground, which increases the erosive effectiveness of the wind.

Winds pick up sediment charges from a variety of sources. The flood plains of streams contribute much, as do the regions of seasonal or perennial dryness where vegetation is sparse or absent; and mountain areas above the tree line also contribute a limited amount. The explosive eruption of volcanoes throws a large volume of fragmental materials into the air. It is stated that volcanic dust thrown

into the air by the eruption of Krakatao, in the Dutch East Indies, had encircled the earth fifteen days after the eruption. Following that explosion, the sunsets all over the earth were unusually brilliant for a period of three years, indicating that much of the volcanic dust stayed in suspension during that period. Man, also, through his various activities, makes direct contribution to the dust content of the air, as anyone who lives in the haze of an industrial town or who drives over a dirt road will agree. Indirectly, through unwise or injudicious land use, man has "accelerated" wind erosion. Although the geological work of winds in humid regions is relatively minor as compared with the work of running water, the total amount of solids carried by winds is large indeed. Udden[2] long ago estimated that in the Mississippi Valley region alone, winds shift more than 850 million tons of sediment an average distance of 1440 miles per year. Although the accuracy of the specific figure is doubtful, the volume of wind-shifted soil is undoubtedly huge.

The engineer encounters wind deposits at various places and is locally concerned with the control or retardation of wind erosion and transportation. The use of snow fences is a familiar example of engineering attempts to regulate wind deposition.

***Wind Erosion.*** Unless armed with solid particles wind erosion is minor. Where charged with solid particles, however, natural sand blasts are highly abrasive. Chepil's[3] experiments on soil illustrate the point. Results of one of his series of experiments is shown in Table 15.1. It has been noted in deserts that the movement of sand grains in a sandstorm is principally within 6 feet of the surface and that by far the bulk of sand is transported within 3 feet of the ground. Dust particles, on the contrary, are elevated to greater heights, often several thousand feet. As the size of a particle diminishes, its surface area relative to volume greatly increases. Thus, for a spherical grain of quartz, 0.03 mm. in diameter, suddenly projected into an air stream of 33 miles per hour velocity, the force

[2] Udden, J A, "Dust and Sandstorms in the West," *Pop Sci. Monthly*, Vol 49 1896, pp 655 664

[3] Chepil, W S, "Dynamics of Wind Erosion," *Soil Science*, Vol. 61, 1945, p 168 *et seq*.

TABLE 15.1.* EROSION OF SOIL BY WIND WITHOUT SAND AND LADEN WITH SAND

| Soil Type | Wind Velocity at 12-inch Height | Amount of Soil Removed by Wind | |
|---|---|---|---|
| | | Without Sand † | With Sand ‡ |
| | (m.p.h.) | (gm/sq m) | (gm/sq m/min) |
| Hatton fine sandy loam | 18.4 | 0.45 | 11.15 |
| | 22.0 | 0.61 | 13.05 |
| Haverhill loam | 16.3 | 0.97 | 7.15 |
| | 22.0 | 1.49 | 11.19 |
| Cypress clay loam | 15.7 | 0.01 | 7.37 |
| | 22.0 | 0.21 | 11.60 |
| Fox Valley silty clay loam | 19.8 | 0.18 | 2.74 |
| | 22.0 | 0.48 | 5.29 |
| Sceptre clay | 22.0 | 0 | 0.50 |

* From Chepil, "Dynamics of Soil Erosion," *Soil Science*, Vol. 61, 1945, p. 169.
† Amounts removed up to the time soil drifting ceased.
‡ Rates of soil movement after cessation of removal by wind without sand.

of air on it is five hundred times the weight of the sphere.[4] Small particles therefore travel essentially with the wind and are deflected with the air stream about an obstruction. Collisions are less frequent than with the transport of large particles, and abrasive effects both on the particles and on obstructions is less. The erosional effect of wind consequently is concentrated at the base of an obstruction rising above the general surface of the ground. Undercut telephone poles and basal abrasion of other objects graphically illustrate the locus of abrasional effectiveness (Fig. 15-9). The lowering of a land surface by wind removal of solid particles is called *deflation*. Except where localized sand blasts are at work, however, the particles picked up and transported by the wind are those prepared for removal by chemical or mechanical weathering, which are parts of either the residual or transported regolith.

The effect of winds on engineering works has been of particular concern in recent years. A velocity pressure (in pounds per square foot) from gusts up to 100 miles per hour amounts to approximately

[4] Bagnold, R. A., *The Physics of Blown Sand and Desert Dunes*, Morrow: New York, 1941, p. 12.

26 pounds per square foot. The total uplift force on a flat-roofed building is approximately one and a half times the velocity pressure. Thus an anchorage of 40 pounds per square foot gives a fair margin of safety except under the most extreme conditions. A value of 30

FIG 15 9 Wind erosion (Courtesy of Pikes Peak Information Bureau)

pounds per square foot has been used for anchorage of many flat-topped factory roofs.

The failure of bridges and the necessity of designing radio towers perhaps as much as 2000 feet tall in the near future make wind forces of especial interest to engineers.[5] For very tall structures like some of the modern towers, wind loads must be carried by guys and stiffening members. The anchorage of structures requires geological insight into the character of the bedrock.

***Wind Deposits.*** Deposition of wind-borne sediment takes place where the velocity of a wind current drops below that required to maintain movement of the solid loads or where precipitation washes the air. Wind-transported dust is universally distributed. Indeed, it has often been said that every square mile of the earth's surface contains wind-blown particles derived from every square mile of the

[5] Sherlock, R. H., "Variations of Wind Velocity and Gusts with Height," *Trans. Am. Soc. Civil Engr.*, Vol. 118, 1953, pp. 463 508.

lands. Mechanical transport by winds, as by streams, consists of tractional dragging or rolling of particles along the surface, suspension, and saltation. The coarse particles, sand size, which move along at or near the surface, locally accumulate into drifts called *dunes;* the fine particles, chiefly of silt size, which are carried in suspension form blanket-like deposits of *loess.*

*Dunes.* Dunes are found near sources of sand available to wind transport. Behind many sandy shores, either marine or lake, elongate dune ridges or narrow, elongate zones of irregular dunes parallel the shore. Along the sandy flood plains of some streams, dunes are found, especially on the leeward side of the valley with respect to prevailing winds. Sandy deserts also display a variety of dunes.

Where free to move unchecked by obstruction, sand builds three primary types of dune and a variety of intermediate or transitional forms. If the sand supply is abundant and winds are moderate, an elongate ridge is built at right angles to the direction of the wind current. These dunes, similar to many snow drifts, are called *transverse dunes.* Other ridges, perhaps because of greater wind velocities or because of obstructions which direct eddies, form with their long axes parallel to dominant wind direction. These are called *longitudinal dunes.* Another type of dune is the crescent-shaped dune, called *barchane,* whose horns point downward. Many irregular and intermediate types exist, whose forms depend upon the strength, duration, and variability of direction of winds, and upon configuration of the surface and its vegetation.

Wind-blown sands are commonly well-graded. However, because of the variability of wind velocities and the development of cross currents, a rather wide range of sizes may be present. Most of the grains of dune sands are between 0.06 mm. and 1 mm. in average diameter, and about 80 per cent between 0.12 mm. and 0.5 mm. The grains of wind-blown sands are commonly rounded, and surfaces frosted and pitted by impact. Cross-bedding is typical of wind-blown sand deposits.

Dunes are either fixed or migratory. The fixed dunes have been stabilized by vegetation which has gained enough density to hold the

sand in place. Migrating dunes have locally traveled considerable distances and have buried forests, buildings, and arable lands. Two methods are in common use for minimizing damage by dune drift. The first is to establish a sand-tolerant vegetation over the dune area. In southwestern France, large-scale dune fixation by this method has made possible the reclamation of some 2,500,000 acres. The second method is to construct wind breaks, similar to the familiar

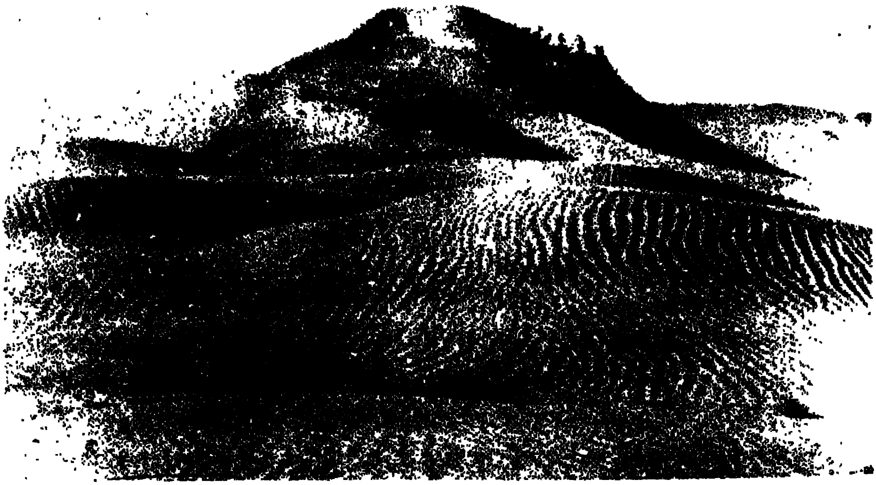


FIG. 15-10. Sand dunes and wind ripple mark. (Courtesy of The Texas Company)

snow fences of the northern states. The first method may be permanent and effective; the second is a temporary expedient.

*Loess.* A deposit of wind-blown dust and silt which typically shows no stratification is known as *loess.* Much, perhaps most, loess is washed out of the air by precipitation. The two principal sources of loess are the dry regions, where the dust is exported by the winds, and the silt deposits of flood plains. During the dissipation of the ice sheets which were formerly extensive in both North America and Europe, much rock flour was washed out from the ice and spread on flood plains of streams which must have been more or less constantly in flood during the melting seasons. Thus correspond-

FIG. 15-11. Deep highway cut in loess. (Courtesy of Iowa State Highway Dept.)

ing to the two principal sources, loess is found chiefly to the leeward of desert regions and on plains or lowland areas peripheral to former ice sheets. The loess deposits of North China, to the leeward of the great dry region of the interior, reach thicknesses of as much as 300 feet. The loess deposits of the Middle West of the United States, in large measure derived from glacial outwash, are much thinner.

The mineral fragments of loess are characteristically angular, and the deposits have a high porosity. One of the peculiar features of loess is its stability in vertical cuts. Cuts that have been sloped back, even to very low angles, are unstable and subject to excessive gullying, sheet erosion, slides, and flows. Current practice, as illustrated in Fig. 15-11, leaves cuts in loess with vertical faces and, if necessary, provides safe disposal of drainage away from the face of the cut.

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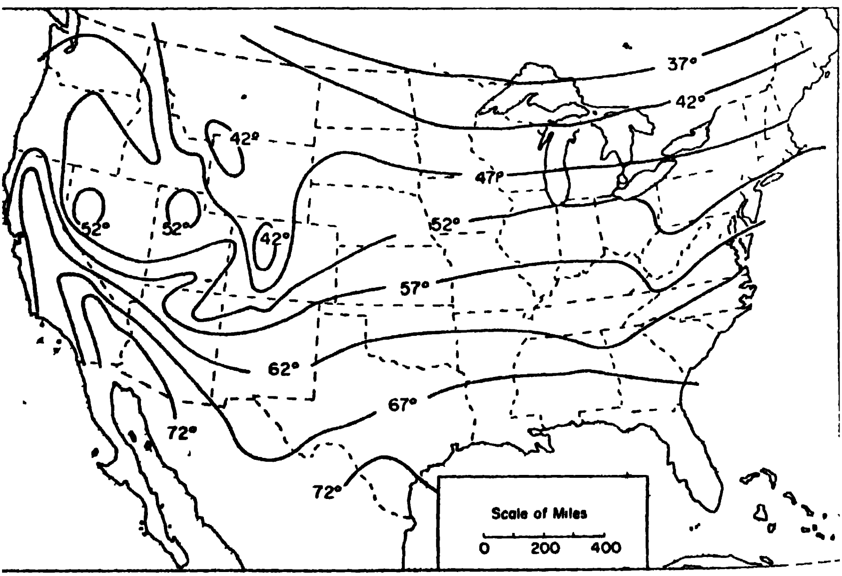



This map shows probable approximate temperatures of well water at depths of 20 to 60 feet. In general the temperature does not vary seasonally more than a degree or two at depths of 30 feet or more. (After U. S. Geol. Survey)

# CHAPTER XVI

# SUBSURFACE WATER

GROUND WATER CONSTITUTES THE MOST IMPORTANT MINeral resource annually extracted from beneath the earth's surface, and certainly no other mineral resource is more vital to life. Much water for domestic, industrial, and agricultural use is taken from streams and natural or artificial lakes. However, a large portion of the water used in homes and industrial plants, and a still larger portion used in agriculture, is obtained from beneath the earth's surface. In the United States, over 35 billion gallons of ground water per day are used, at a cost of over 1.25 million dollars a day. Moreover, most permanent streams are nourished wholly or in part by underground supplies.

The engineer is concerned with ground water when solving problems of water supply, and often he meets subsurface water problems incidental to sanitation, land drainage or irrigation, excavation, foundations, and control of earth movements. Because of the many engineering projects to which underground water is of significance, the engineer should have a good understanding of the principles of its occurrence and movement.

## Sources of Water in the Ground

Subsurface water is derived from several sources; the impurities in it frequently indicate its origin or history.

In part, water in the ground is a direct contribution from magmatic or volcanic activity. During the course of crystallization, water is given off, excluded, that may pass into the adjacent rock

and become part of the underground supply. Water excluded in the crystallization of igneous rocks is called *juvenile water*. Although it is probable that all the water in and on the outer portions of the earth is the result of igneous activity in the geologic past, direct magmatic contributions to the general subsurface water supply are probably negligible. Many ore deposits and mineral veins, however, have been made by juvenile water.

When sediments are deposited beneath the seas, some of the sea water is held in the interstices. Upon deposition of impervious sediment above, some of this water may be imprisoned and retained in the sediment until tapped by accident or intent. Water trapped in sediments at the time of their deposition is called *connate water*. Some of the salty water encountered locally in inland wells, particularly in parts of the Middle West, is connate water.

The most important source of subsurface water is that portion of the precipitation which sinks into the ground. This, the major portion of the underground water, is called *meteoric water*.

Water is drawn into the atmosphere by evaporation and distributed by the winds to all parts of the atmosphere. Where condensation takes place, the water may reach the earth's surface again in the form of rain, snow, hail, frost, or dew. Of the atmospheric water that falls on a land surface, a part is re-evaporated; a part may run off the surface immediately in the form of sheet flood, rills, and streams, and find its way directly into some body of water at a lower elevation; and a part sinks into the ground. Of the part that does sink into the ground, plants utilize some, and plant transpiration returns considerable moisture to the atmosphere. Rock and mineral alteration also uses some of the subsurface water in the production of hydrated minerals—for example, limonite, a hydrated iron oxide Another portion of the water that penetrates the ground sinks downward until it reaches the zone where all openings are saturated. Circulation in the saturated zone is generally very slow, but a part of the water finds its way to the surface again as seeps or springs or through wells. The hydrologic cycle is shown diagrammatically in Fig. 16-1.

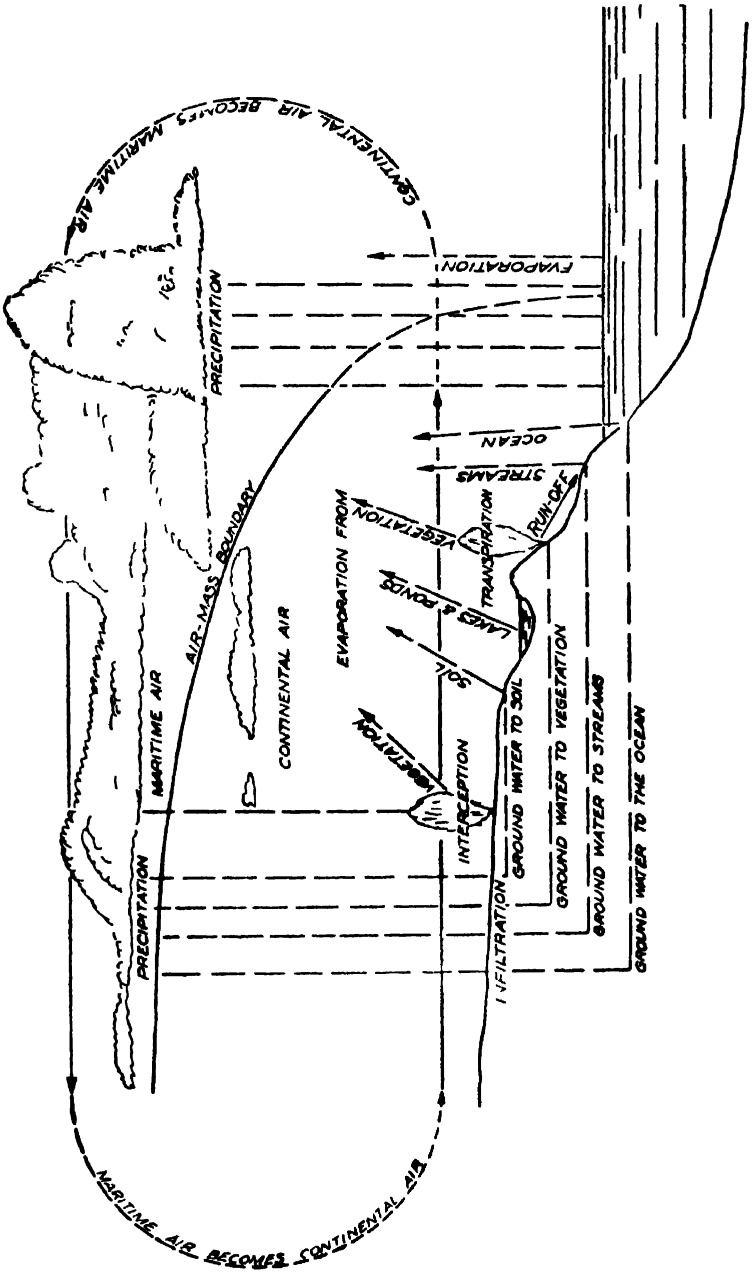



FIG 16 1 The hydrologic cycle (U. S Department of Agriculture) The sun draws 4,300 billion gallons a day and distributes it over the United States. This amounts to 13,200,000 acre feet

## THE GROUND WATER TABLE

The distinction between porosity and permeability has already been emphasized. Pores are intergranular openings of small size, and porosity is defined as the ratio of pore space to the total volume of the rock. *Effective porosity* (*specific yield*) is that part of the void volume that will drain under gravity. Permeability is the capacity of the rock to transmit fluids. It is measured by the quantity of water passing through a unit cross section in a unit time with a hydraulic gradient of 100 per cent. A rock with high porosity, as clay, may have very low permeability In other words, the material may contain a large amount of water but transmit very little. Nonporous rocks, however, are readily permeable if penetrated by many cracks or other openings.

The character and origin of rock openings through which water may circulate have already been described in preceding chapters These openings can be classified as (1) interstitial or intergranular, (2) divisional fissures, joints, faults, shear zones, and cleavages, and (3) vesicles and solution cavities. The unconsolidated and partially consolidated clastic sediments have intergranular openings. The crystalline rocks, i.e., most igneous and metamorphic rocks, have principally divisional openings; the somewhat soluble rocks, principally limestone, dolomite, and marble, in addition to divisional openings often have solution cavities and channel ways; and lavas frequently have not only many fractures but also many vesicles. The larger the size of the openings and the better their interconnection, the more ready is water percolation through them. Openings of all types are more abundant within a few hundred feet of the earth's surface than at great depths, although, locally, fractures and openings penetrate much deeper. At great depths, the weight of overlying rock precludes the existence of openings through which water can circulate readily although, exceptionally, water-bearing fissures have been encountered at depths as great as 6000 feet.

At variable distances below the surface, the rock openings are saturated with water. The top of the saturated zone is called the

*water table.* Above the water table the circulation is dominantly downward and comparatively rapid; below the water table, circulation is determined by the slope of the water table surface and is comparatively slow. The zone above the water table, where circulation is active and dominantly downward, is called the *vadose zone,* and the subsurface water within this zone is called *vadose water.* In the vadose zone, oxidation and leaching are general effects of subsurface water, whereas below the water table, deposition and cementation are common. Thus, rocks above the water table are said to be in the zone of weathering, and those below the water table to be in the zone of cementation.

The water table is not a fixed surface; it fluctuates according to the amount of precipitation. In dry years the water table is deeper and flatter than in wet years. The water table presents, in general, a somewhat subdued or softened reflection of the surface topography. The surfaces of most lakes, permanent streams, or swamps mark the position of the water table at that particular place. A few of these water bodies, however, lie above the general water table, held up by some impermeable barrier.

The preceding remarks on the water table are of general application. Because the different types of openings in rock present somewhat different aspects of the water table concept, however, the porous and permeable rocks, the cavernous rocks, and the imporous and permeable rocks are discussed separately with reference to subsurface water. Strictly speaking, the water table concept does not apply to impermeable materials nor to confined water.

### Subsurface Water in Porous and Permeable Sediments

Rocks which are both porous and permeable are principally the clastic sediments, i.e., those sediments that have been deposited mechanically by water, wind, or ice. The principal clastic rocks are gravel, sand, silt, and clay, and their consolidated equivalents, conglomerate, sandstone, siltstone, and claystone (argillite). The porosity of gravel and sand ranges roughly from 25 to 40 per cent. Because of the relatively large size of the pore spaces and their interconnec-

tions, these rocks are readily permeable Silt, much of which has a porosity between 30 and 50 per cent, is less permeable than sand because of the smaller openings, and clay with porosity commonly between 40 and 70 per cent, is relatively impermeable. Admixtures of sizes generally show the permeability characteristics of the finer grades present Cementation or consolidation of the clastics reduces both void space and permeability Recently deposited, geologically young limestones, also, are frequently so permeable and porous as to belong to this group

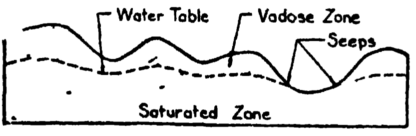



FIG 16 2 The water table in clastic sediments

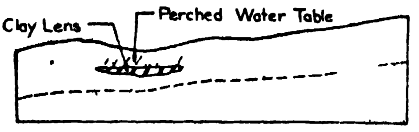



FIG 16 3 Perched water table

***The Water Table.*** The ground water table in porous and permeable sediments is generally a subdued reflection of the surface topography The slower the percolation of water through the material, the more truly the ground water surface reflects the topography If the precipitation of a humid region ceases for a long enough period inequalities in the ground water surface tend to disappear, the level drops and evens out With continued drought, it would eventually become a near plane surface In dry regions the water table does not so faithfully parallel the surface irregularities Fig 16 2 illustrates, diagrammatically, water table conditions in clastic sediments It will be noted that the water table lies nearer the ground surface in the valleys than it does in the highlands Thus, although tending to parallel the surface topography, the parallelism is imperfect If the sediment has capillary openings, a capillary fringe of water above the water table is present Above the general level of the water table, also, impervious layers or lenses of limited extent locally cause a *perched water table*, as shown in Fig 16-3. If the perched water table is near enough to the ground surface to cause a wet or swampy tract, drainage often is accomplished most economically by driving drainage wells through the impervious layer.

***Water Table Maps.*** Water table maps are often useful. Commonly, these depict the configuration of the water table by contours. Observations on the water levels of wells or bore holes supply data for these maps. In the Kansas River Valley, resistivity measurements are estimated to give the depth of the water table to within an aver-

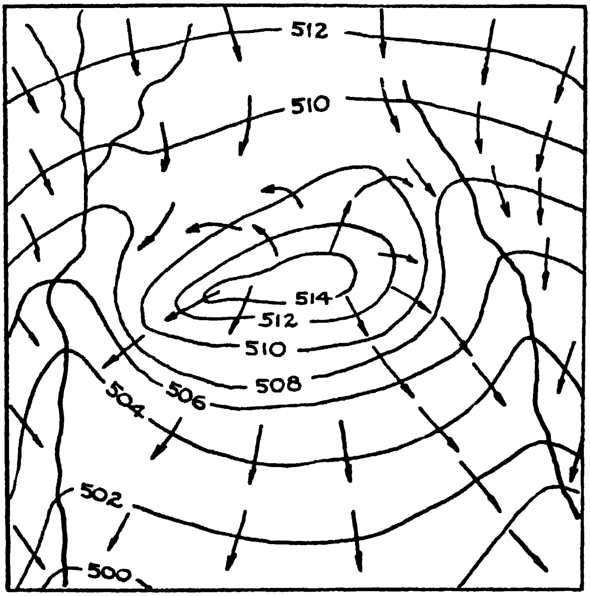



FIG. 16-4 Water table map, showing elevations of the water table and the directions of flow. (Courtesy of Edward E. Johnson, Inc.)

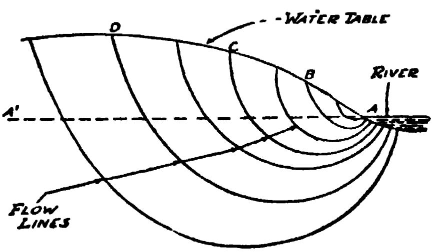



FIG. 16-5. Configuration of lines of flow through a homogeneous, permeable material—section. (From Rhodes and Sinacori, *Journal of Geology*, Vol. 49, 1941)

age error of 15 per cent. In some areas existing wells are numerous enough to give sufficient data; in other areas existing wells are too few, and supplementary bore holes must be made. Electrical methods (page 236) also can be applied in some areas to the determination of the water table. A water table map shows the elevations at the time

of measurement. The levels fluctuate with precipitation and withdrawals, however, and a series of maps based on periodic observations may be necessary. In gathering data from well observations, it is necessary to distinguish between water table levels, which indicate the upper limits of the zone saturated by free water, and pressure levels, which indicate the limits of rise of water confined in the ground under head.

Water table maps indicate areas of infiltration or recharge, for where the water table lies below the ground surface, water penetrates the ground. This seepage is *influent.* The water table may coincide with the ground surface. Many valleys, for example, intersect the water table, and *effluent* seepage feeds many streams. Many swamps and permanently moist soil areas likewise mark the ground water surface, and most lake basins reach the water table. Some swamps, lakes, and streams, however, are perched above the water table. If they lose water to the ground, they are *influent.*

Water table maps are also of use in analyzing the direction and rate of ground water movements (Figs. 16-4 and 16-5), whether natural or induced by the works of man. The slopes of the ground water table vary inversely with the permeability of the ground; the more permeable the ground, the lower is the water table slope. In a rock of given permeability the water table slope varies according to the velocity of percolation; stated otherwise, the velocity of percolation varies directly with the slope angle.

***Fresh and Salt Water Relations in Coastal Areas.*** In coastal areas, the relationship between fresh and salt water in the ground is of both interest and practical significance. It has long been noted that wells in sediments close to the sea margin commonly yield fresh water. Investigations along the sandy coasts of Holland led to the discovery that fresh water occurs in the ground at considerable depths below sea level, and that a quite definite relationship can be expressed between the elevation of the water table and the depth to which fresh water extends below sea level. The fresh water floats on salt water, but because of the small difference in densities the fresh water extends to rather surprising depths. The column of

fresh water is balanced by a column of salt water in a manner similar to the floating of an iceberg or to familiar laboratory experiments with liquids of different densities in U tubes. Fig. 16-6 diagrams the relation. In this figure, the height of the column of salt water, $h$, balances a fresh water column $H$. If $t$ is equal to the elevation of the water table above sea level, then $H$ is equal to $h + t$, and if $g$

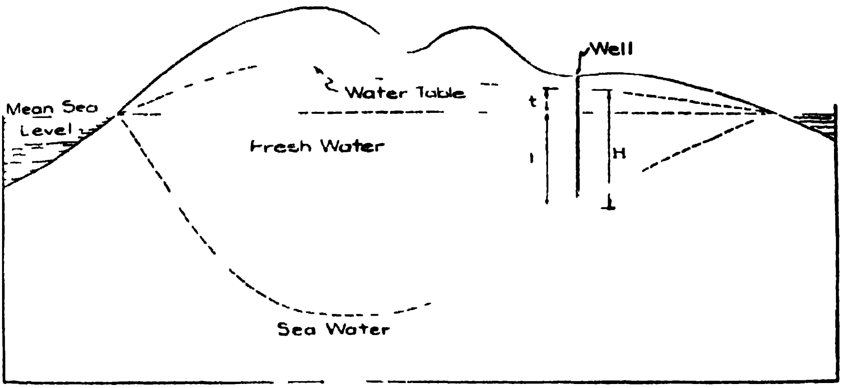



FIG. 16-6 Fresh and salt water relations in readily permeable materials

is the specific gravity of the salt water, $H$ is equal to $hg$. Hence, algebraically:

$$t = h\ (g - 1) \quad \text{or} \quad h = \frac{t}{g - 1}$$

The specific gravity of sea water is somewhat variable, but each foot between the water table and sea level indicates approximately 10 feet of fresh water below sea level. It should be noted, however, that if the length of the fresh water column is reduced locally, as by pumping from a well (draw-down), a salt water cone of intrusion is developed, which is steeper than the cone of depression caused by the pumping. A permanent lowering of the water table of 1 foot involves a rise of salt water of some 40 feet.

***Movement of Subsurface Water.*** The flow of a liquid is either laminar or turbulent. In laminar flow the movement is orderly and streamlined; in turbulent flow, irregular eddies and movements take place. Laminar flow, which occurs at very low velocities, prevails in

the movement of underground water. The laminar flow of sub surface water through rock is called *percolation*. Because little energy is lost in the production of eddies, the velocity of percolation varies directly with the hydraulic gradient and inversely with the permeability. Darcy's law states:

$$v = \frac{kh}{l}$$

where $v$ (velocity) is the rate of flow of water passing through a cross-sectional area normal to the direction of flow, $k$ is the *coefficient of permeability* which represents the velocity for a hydraulic gradient of unity for a particular material, $h$ is the difference in head between the ends of a considered soil column, and $l$ is the length of the con

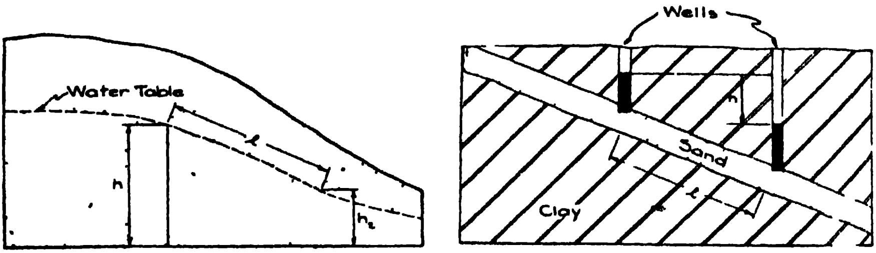



FIG 16 7 Diagrammatic illustration of Darcy's law *left*, free water; *right*, confined water

sidered soil column (Fig. 16-7). The hydraulic gradient, $h/l$ is conventionally expressed as $i$; hence, Darcy's law is often written.

$$v = ki$$

and accordingly the volume of water moving in unit time through a considered area $A$ is:

$$q = kiA$$

However, the percolation is through only the void space of the considered area; hence, the seepage or percolation velocity is greater than $v$ of the formula above The percolation velocity, $v_p$, is consequently:

$$v_p = \frac{v}{n}$$

where $n$ is the percentage of the area occupied by voids (porosity). The velocity units are the same as those expressed in the coefficient of permeability—e.g., feet per day or cm/sec.

Following the usage established by the U. S. Geological Survey, Civil Engineers often state Darcy's law as:

$$v = K_p \frac{h}{l \times 7.48 \times V_p}$$

where $v$ is flow in feet per day, $K_p$ is rate of discharge in gallons per day at 60°F, through a cross section of 1 square foot under a unit hydraulic gradient (1 foot per foot); $h$ is the difference in head between the ends of the considered soil column (in feet); $l$ is the length of the considered soil column (in feet), and $V_p$ is the soil porosity (per cent); while 7.48 is the number of gallons per cubic foot. In computing $K_p$ from the movement of dyes introduced into the ground water, the *specific yield* ($y_s$) should be substituted for $V_p$. The specific yield is the volume of water free to drain under gravity expressed as a percentage of the total volume. A *field coefficient of permeability*, $K_f$, in use by the U. S. Geological Survey is defined as the rate of flow in gallons per day through each foot of thickness of a given aquifer in a width of 1 mile under a gradient of 1 foot per mile. The field coefficient multiplied by the thickness of the saturated part of the aquifer gives a convenient term called the *coefficient of transmissibility* which expresses the ability of the aquifer as a whole to transmit water.

Various methods of determining the coefficient of permeability are used. Laboratory methods must use undisturbed soil samples to be applicable or useful, but the techniques are simple and the laboratory determinations easily made. Field methods to determine permeability, when and where possible, are probably preferable to laboratory determinations because they average out inhomogenieties present in most natural permeable media. The techniques and equations used are presented in textbooks of soils mechanics and hydrology.

Darcy's law has been widely used and has been demonstrated to

be essentially correct for laminar flow. The constant $k$ must be established by laboratory or field investigation for each material to which the law is applied. It should be remembered that in nature, regularity is the exception rather than the rule. Irregularities in sedimentation, variations in the state of packing of the sedimentary particles, and variations in the degree of cementation as well as variations of structure are to be expected. The permeability of natural sediments is therefore variable in different directions. Permeability across the bedding is commonly less than that parallel to the bedding Many permeable beds are interstratified with relatively impermeable beds. Lateral variations in the state of packing and lateral variations in grading and lithology, as well as vertical variations, are common. In a heterogeneous rock series, therefore, caution is necessary in applying any formula to ground water flow. Where the material is naturally homogeneous or has been emplaced uniformly or under close control by man, determination of permeability coefficients and application of Darcy's law are justified and the results are often invaluable.

The Ground Water Division of the United States Geological Survey, in the laboratory testing of some 2000 natural earth aggregates, found that the most permeable material tested transmitted water at a rate some 450 million times that of the least permeable material tested under the same hydraulic gradient. Figures for the average rates of ground water movement are, consequently, difficult to give and of limited value Subject to very wide deviations and presented as of suggestive value only are the following approximate limits (hydraulic gradient 100%):

| | |
|---|---|
| Gravel | 1000 to 10,000 feet per day |
| Sand | 100 to 1000 feet per day |
| Clay | 5 feet per day to practically nil |

or in metric units, on a log scale, common values of permeability $k$ (cm $sec^{-1}$) are shown in Table 16.1.

TABLE 16.1.* PERMEABILITY AND DRAINAGE CHARACTERISTICS OF SOILS

| $k$ (cm/sec$^{-1}$) | $10^{2}$ $10^{1}$ 1 | 1 $10^{-1}$ $10^{-2}$ $10^{-3}$ | $10^{-4}$ $10^{-5}$ $10^{-6}$ $10^{-7}$ | $10^{-7}$ $10^{-8}$ $10^{-9}$ |
|---|---|---|---|---|
| Drainage | Excel-lent | Good | Poor | Practically Impervious |
| Soil | Clean gravel | Clean sand, Clean sand and gravel mixtures | Fine sand, silt, mixtures of | Homogenous clay |
| | | | sand silt and clay, till, stratified clays | |

* After Casagrande and Fadum.

## SUBSURFACE WATER IN CAVERNOUS ROCKS

Rocks with cavernous types of openings transmit water freely if the cavernous spaces are interconnected. Many cavernous rocks are so permeable as to be virtually stone sieves. The largest subsurface openings known belong to this class. Cavernous openings range in size from the small vugs and vesicular openings of lavas to the giant caverns and tunnels of limestones, miles in length. Two groups of rocks, the soluble rocks and the volcanic lavas, have openings of the type classed here as cavernous.

***Soluble Rocks.*** Meteoric waters which carry carbon dioxide, oxygen, and locally organic acids move downward through the vadose zone dissolving and decomposing many minerals; the carbonate minerals especially are susceptible to solution. In the carbonate rocks, therefore, the limestones, dolomites, and marbles, there is frequently a well-developed drainage system of interconnected joints enlarged by solution. Locally the avenues of percolation are enlarged to caverns or tunnels; thus in many limestones a true system of underground streams is established comparable to a system of surface streams. The maximum effects of solution are in the vadose zone. In this zone, joints and fractures leading downward from the surface are locally enlarged by solution. The chimney-like openings which result are called *sink holes* (Fig. 16-8). Not all sink

holes are formed by joint enlargement; many are formed by the roof failure of caverns or tunnels, the arches of which have either become too broad to be self-supporting or have reached too close to the surface. Many though not all sink holes lead into underground rooms, tunnels, or subsurface streams.

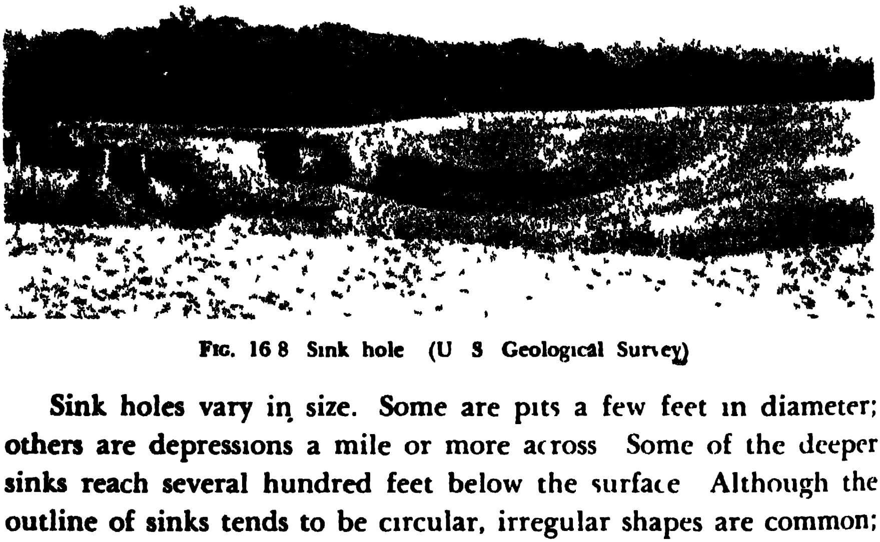
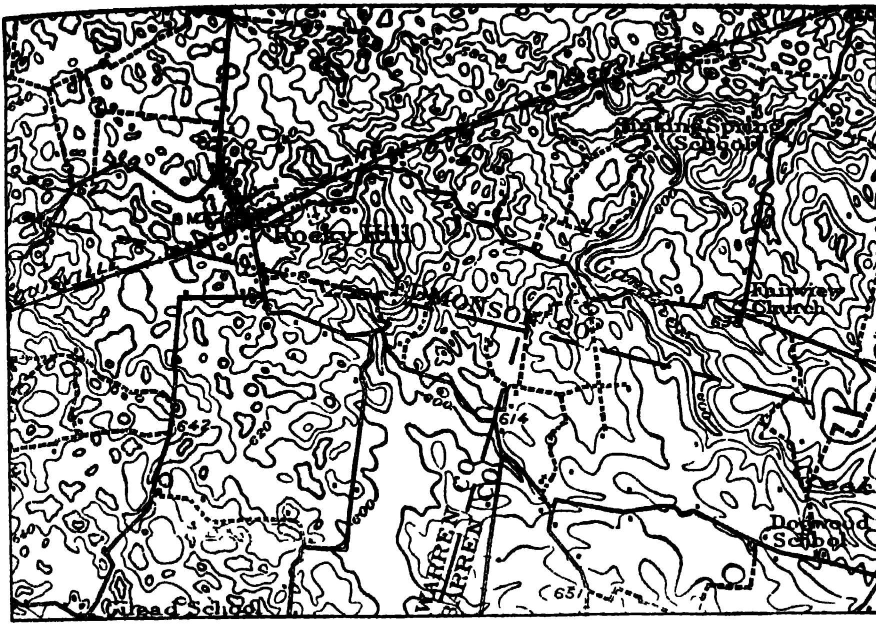


FIG. 16 8 Sink hole (U S Geological Survey)

Sink holes vary in size. Some are pits a few feet in diameter; others are depressions a mile or more across Some of the deeper sinks reach several hundred feet below the surface Although the outline of sinks tends to be circular, irregular shapes are common; the walls may be overhanging, vertical, or of gentle slope. Sinks are rock-rimmed; if, however, the side walls are of gentle slope, soil and vegetation may mantle both slopes and floor. Many sinks reach the water table and are occupied by lakes or ponds.

Where sinks are abundant, the terrain is characterized as *karst topography*. In karst areas, surface streams are few; the drainage is chiefly underground. An area of typical karst topography is shown in Fig. 16-9. In the United States, the karst areas of Florida, Kentucky, and Tennessee are well known. Mark Twain's description of the underground drainage-ways of the Hannibal, Missouri, district is familiar to all readers of *Tom Sawyer*. In a karst area, turbulent




*After U S Geol Survey*

FIG. 16 9. A section from Mammoth Cave, Kentucky, topographic map, showing Karst topography with sinks, depressions, disappearing streams and small hills Scale: approximately 1 inch equals 1 mile. Contour interval, 20 feet.

underground streams erode, transport, and deposit in the same way as do surface streams.

A karst area may be likened to a stone sieve or, better, to a stone sponge. The permeability because of interconnected solution channels is often very high, and the water table, consequently, is comparable to that of permeable granular sediments. In fact, when studying possible effects of the proposed Florida Ship Canal, Paige[1] considered the ground water reservoir of the solution honeycombed *Ocala* limestone, which underlies much of the peninsula, comparable to a reservoir of permeable sand or gravel in a coastal area, and he applied the Herzberg formula (page 355) to determine the thickness of the fresh water prism floating on salt water. Overlying beds of less permeable sediments give local artesian conditions which

[1] Paige, Sidney, "Effect of a Sea Level Canal on the Ground Water Level of Florida," *Econ. Geol.*, Vol. 31, 1936, pp. 537 570.

complicate the problem. In this study, Paige[2] estimated the changes in the water table which would be produced by the intersection of the water table by the sea-level canal cut. Essentially, he did this by studying existing gradients in the water table under comparable conditions, drawing similar curves which might be expected to develop along the canal cut, and deducing the distribution of effects back away from the canal line. The paper by Paige, already cited, and the subsequent discussion and reply[3] its publication invoked give an excellent example of ground water studies applied to a major engineering project.

***Water in Volcanic Rocks.*** Many lava flows are so "slaggy," vesicular, and cavernous as to be comparable in permeability and water

FIG. 16-10. Water issuing from leaky basalt at Thousand Springs, Idaho. (U. S. Geol. Survey)

content to cavernous and leaky limestones (Fig. 16-10). Not only are lava flows themselves often readily permeable, but associated and interbedded pyroclastics, cinders and unaltered ash likewise are

[2] *Ibid.*, pp. 565-568.

[3] Brown, J. A., "Effect of a Sea Level Canal on the Ground Water Level of Florida—A Discussion," *Econ. Geol.*, Vol. 32, 1937, pp. 589-99; Thompson, Meinzer, and Stringfield, "Effect of A Sea Level Canal on the Ground Water Level of Florida," *Econ. Geol.*, Vol. 33, 1938, pp. 87-107; Paige, Sidney, "Effect of a Sea Level Canal on the Ground Water Level of Florida—A Reply," *Econ. Geol.*, Vol. 33, 1938, pp. 617-665.

often very permeable. In general, basic flows are more permeable than acid flows. The openings are of several types: lava tunnels, openings at the base of flows, gas bubble cavities, tree molds, and joints.

Lava tunnels are the largest openings in this type of rock. The tunnels are formed where the top of a flow crusts over, permitting the still liquid lava beneath to flow out. Although these tunnels lack the continuity and extent of many limestone tunnels, they are comparable.

The most permeable zones of lava flows are at their basal contacts. Seldom does the lava mold itself completely to the surface over which it flows. Because the tops of many lava flows are very jagged and irregular, and often excessively cracked and slaggy, later flows over the surface leave many openings. The bottom of an overriding flow is often partially congealed and, thrust along by the moving lava, is slaggy, thus adding to the permeability of the contact zone. Many similar but less pronounced zones of permeability are found at the contacts of flows and sediments.

Vesiculation of lava due to the escape of gas renders the tops of many flows excessively porous or scoriaceous; near the lava source, vesiculation is often especially well displayed. The permeability due to vesiculation depends upon the degree of interconnection of the vesicles. The openings are of varying dimension; often the range is from a fraction of an inch to several inches. The shape of the vesicle is often tubular.

Cavernous openings, not so widespread but locally important, are the molds of trees, overwhelmed by lava which hardened before the wood was completely burned away.

Lavas are subject to rapid cooling; contraction joints, therefore, are abundant. Most volcanic areas are seismically unstable, and faults, likewise, are abundant in lavas. The intrusion of impervious dikes and alteration of volcanic ash beds to impervious clay complicate the hydrology of volcanic areas. Fig. 16-11 shows schematically the occurrence of subsurface water in the Hawaiian Islands, a volcanic area.

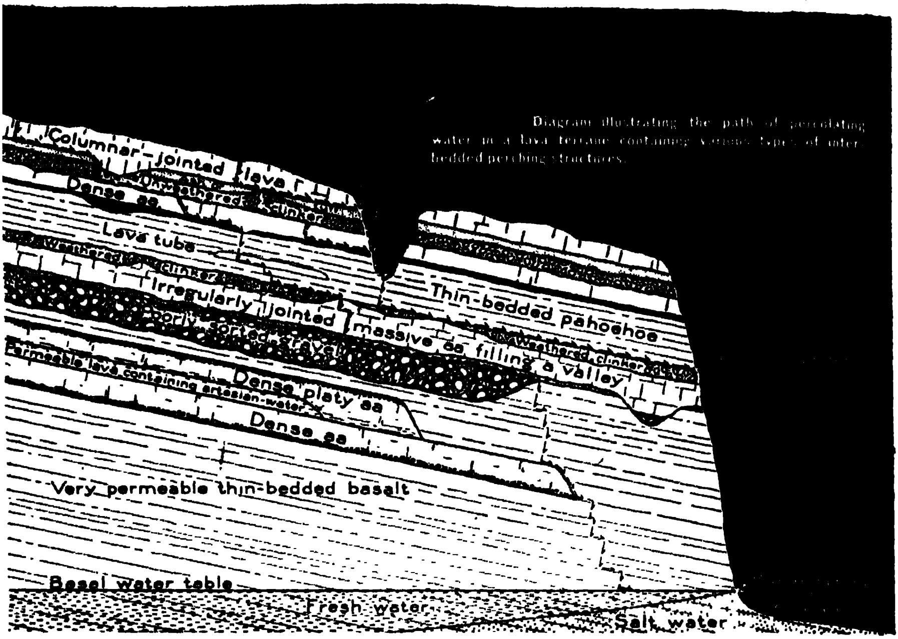



FIG. 16-11. Typical occurrence of ground water in the Hawaiian Islands, a lava terrain. (From Stearns and McDonald, Division of Hydrography, Hawaii.)

## SUBSURFACE WATER IN ROCKS WITH DIVISIONAL OPENINGS

All consolidated and some unconsolidated rocks have fractures or partings dividing the rock mass into units of various size. These structures, joints, faults, shear zones, and cleavages are here called *divisional openings*. In crystalline rocks—granites and related varieties, gneisses, schists, and quartzites—in nonvesicular volcanics, and in the thoroughly cemented sediments, water is chiefly in divisional openings. The origin of these fractures and partings has been previously described. They are both *tectonic*, the result of deep-seated earth stresses, and *katamorphic*, the result of mechanical and chemical changes near or at the earth's surface. Because the pressure due to weight of overlying rock load increases with depth, fractures deep below the surface tend to be blind or tight; yet some readily permeable fissures extend to great depths. Many more open partings and fissures, however, occur in the zone between the surface

and two or three hundred feet down than occur at greater depth; consequently, the bulk of the water in rock fractures is comparatively near the surface.

FIG 16 12 Subsurface water issuing from cracks in granite.

Sheet jointing is well developed in most large intrusive masses. Complementary sets of steeply dipping joints are found also in most intrusions, although the spacing, of course, is variable (Fig. 16-12). Shear zones (Fig. 16-13), frequently exposed in quarries and cuts, are the best water-yielding structures of massive rocks. Localized weathering has enhanced the permeability of many shear zones.

Volcanic rocks, because of their rapid cooling, are generally highly jointed. Indeed, the joint net in many lavas is so close that blocks greater than a foot in diameter cannot be recovered. Columnar joints, if present, give ready access to water, and less regular but more common joints do likewise. Lavas have also many fault and crush zones.

FIG. 16-13. Shear zone in granite.

Gneisses and schists have surficial joints due to weathering, and many have tectonic joints of more or less irregular pattern. These rocks, in addition, frequently have joints parallel to the foliation or schistosity along which water can seep. The planes of schistosity carry some water, especially in the surficial zones where they have been somewhat opened.

Slates, in addition to joints and local fault zones, have flow and fracture cleavages which carry water. Shales and other argillaceous rocks and thoroughly cemented sediments have little intergranular permeability, but divisional openings are always present. Most sediments have bedding plane joints. In many sediments, also, there are found joints inherited from the diagenetic stage. These resulted from shrinkage, compaction, and slump of the unconsolidated and semiconsolidated sediment.

Quartzites have joints and fracture systems similar to those of the massive igneous rocks.

The water table concept for rocks whose permeable openings are of the divisional type is somewhat different from that presented for rocks of intergranular permeability. The water table in these rocks is more irregular and does not reflect the topography as faith-

fully. Insofar as the divisional openings are supercapillary in size and are interconnected, there is a water table, nevertheless. This variation of the water table is shown diagrammatically in Fig. 16-14. In this diagram it will be noted that success in well location depends

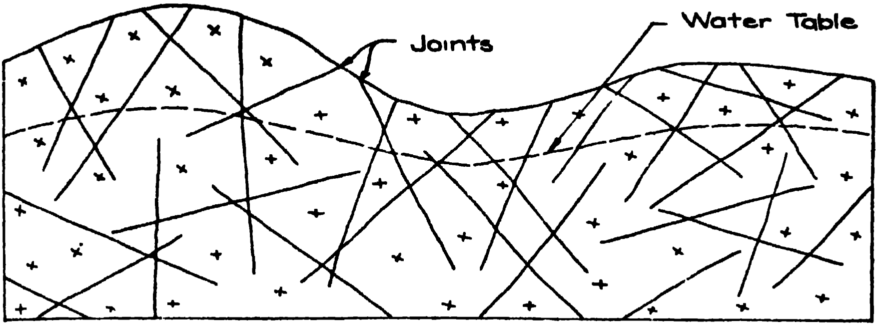



FIG. 16-14 The water table in rocks with interconnected divisional openings

on the chance of intersecting a sufficient number of water-bearing structures to gain the required yield. Thus, although chance is an important element in drilling formations with divisional openings, judicious selection of well site based on observation of the distribution and attitude of the openings and structures of surface exposures increases the percentage of successful wells of moderate depth.

Note has been made of the increasing tightness of divisional openings with depth and also of the greater number of joints within the shallow depth zone. Therefore, if a well being driven in rocks with these structures does not yield somewhere near the required flow at a depth of some 200 feet, the chances of success are better if a new hole is started near by, say 100 or 200 feet away, than if the unsatisfactory hole is deepened.

The divisional openings of most rock masses yield sufficient water for domestic purposes at depths of less than 200 feet. Probably ninety out of a hundred wells in granite, for example, will yield more than 2 gallons a minute and the average yield will be nearer 10 gallons per minute. In slate the percentage of success is somewhat higher. In the crystalline rocks of Connecticut the average yield

of 123 wells with an average depth of 108 feet is 12.7 gallons per minute.[4]

## ARTESIAN WATER

At many places ground water is held in a permeable zone by impermeable rock on two sides. The water is *confined*, and the permeable zone is an *aquifer*. In many places confined water is under head and hence will rise in a well which taps it. Confined water under hydrostatic head is called *artesian* water, and a well in which the water rises above the adjacent ground water level is called an *artesian well.*

The conditions necessary for artesian flow are:

1. An aquifer, or permeable zone or bed.
2. Relatively impermeable rocks above and below which confine the water in the aquifer.
3. Sufficient dip of the aquifer to give an hydraulic gradient.
4. An intake area such that the aquifer may be charged.

These conditions are shown diagrammatically in Fig. 16-15 Impermeable rock above and below is necessary to insure against loss of head. The inclination of the beds gives rise to a hydraulic gradient which extends from the level of saturation down the dip of the structure as far as the structure continues. Artesian water may be met in rocks of all types of openings. Divisional openings or shear zones in the crystalline rocks frequently give rise to artesian flow when penetrated. More commonly, however, artesian water is found in permeable sandstone layers intercalated with impermeable shales or other types in a sedimentary rock series.

Several areas of the United States draw heavily on artesian water. Along a part of the eastern margin of the Rocky Mountains, the upturned edge of the so-called *Fountain sandstone* outcrops. It is a good aquifer, being both porous and permeable. This sandstone dips

[4] Gregory, H. E., and Ellis, E. E., "Underground Water Resources of Connecticut, with a Study of the Occurrence of Ground Water in Crystalline Rocks," *U. S. Geol. Survey Water Supply Paper 232,* 1909, pp. 91-94.

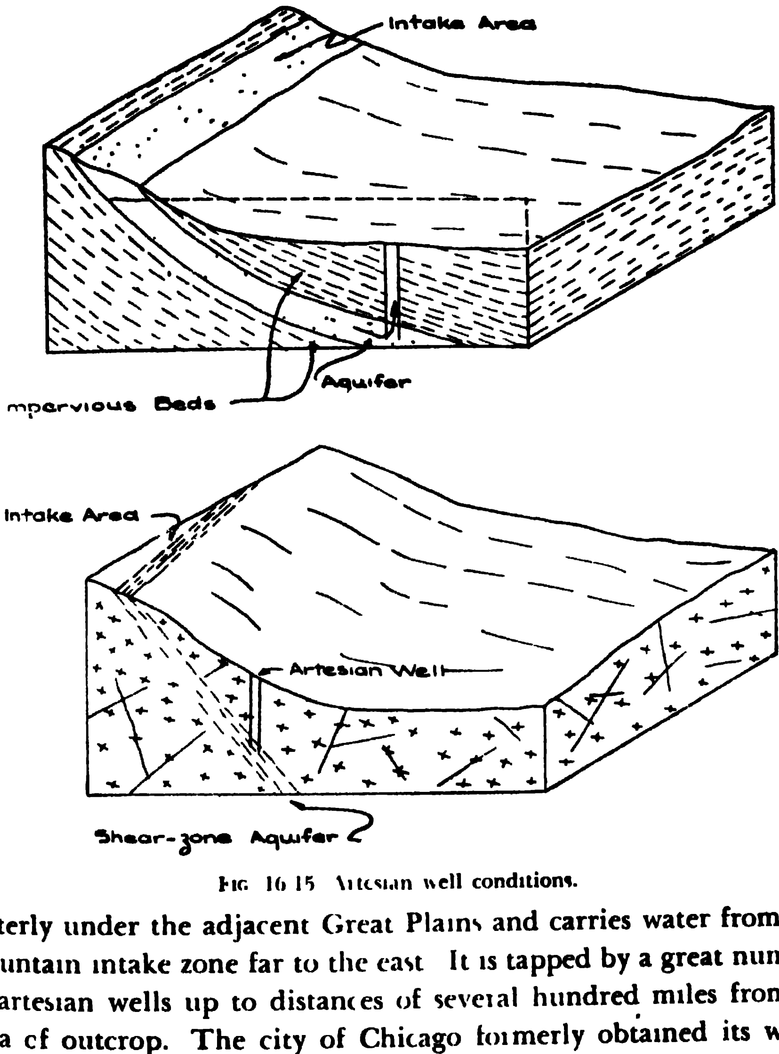



FIG. 16.15 Artesian well conditions.

easterly under the adjacent Great Plains and carries water from the mountain intake zone far to the east. It is tapped by a great number of artesian wells up to distances of several hundred miles from its area of outcrop. The city of Chicago formerly obtained its water supply from a Cambrian sandstone which outcrops in Wisconsin and dips gently to the south. Rain that falls on the Wisconsin intake area is estimated to require some two hundred years to travel to the Chicago area. A similar condition is found in the central part of the United States, where the *Roubidoux sandstone* outcrops on the Ozark Dome and, dipping gently north, carries water into the central and northern part of Missouri where it supplies a number

of cities with water. The city of Greenville, Maine, formerly obtained water from an artesian well that penetrated a fracture zone in slate.

## Springs and Wells

Man's first drink of ground water undoubtedly came from a spring. An obvious step was to dig out and improve the spring. Perhaps with spring failure, primitive man dug deeper at the spring site, or perhaps he found that springs could be made by digging shallow holes at damp spots. In any event, before the dawn of history man had learned to dig for water and thus had taken one more step in turning the resources of nature to his own welfare.

***Springs.*** The natural emergence of subsurface water takes place as *springs* or *seeps*. In springs the emergence is localized about a point; in seeps the emergence is spread out. A variety of geological conditions give rise to seeps and springs. Springs can be classified, accordingly, into water table springs, contact springs, cavernous rock (karst) springs, and structural springs.

*Water table springs* and *seeps* are found where the ground surface intersects the water table. Many occur around the margins of lakes or other depressions and along the slopes of a stream valley. In the humid regions, most permanent streams receive at least a part of their water from the ground water reservoir. Few streams flow the year around until they have eroded their channels deep enough to intersect the water table. Most wells are artificial springs of this category, and many excavations, as along highways or elsewhere, develop this type of spring or seep.

Where a relatively impermeable bed underlies a bed of greater permeability, the underground water tends to move down the dip slope of the contact. If the contact is exposed by erosion or excavation, *contact springs* or *seeps* are formed. Contact springs are often found at the contact between the unconsolidated soil and the bedrock surface. In glaciated regions, this type of spring is often found where erosion has exposed the contact between relatively impermeable till deposits and overlying stratified drift. Springs of this type,

also, are noted frequently emerging from beneath a talus or landslide deposit, or at the base of an alluvial fan.

Excavation or erosion in cavernous rocks locally taps underground water. Some of the largest flowing springs of the world are of this class, where real underground rivers emerge. Many springs from cavernous basalts and limestones are known which discharge more than 100 cubic feet per second. Silver Springs, Florida, for example, has a flow of more than 800 cubic feet per second. If the cavernous rock from which the water emerges is limestone, the spring may be called a *karst spring*.

Divisional openings may lead ground water to the surface, where it emerges sometimes under head as a *structural spring*. Springs and seeps of this class are frequently seen in quarries or along rock cuts.

Springs are also often classified in other ways. Mineral springs and thermal, or hot, springs are so widely known as to deserve mention.

Most springs are mineral springs in the sense that the water contains dissolved mineral matter. If the dissolved mineral content reaches a concentration sufficient to impart either a noticeable taste or smell, or if the dissolved mineral content is of unusual substances, the spring becomes popularly known as a *mineral spring*. The waters of some springs are abnormally radioactive.

Meteoric water is heated if it reaches warm or hot rock beneath the surface. If the heated water emerges, it is a *hot spring*, or *thermal spring*. Many thermal springs are found in regions of present or recent volcanic activity. Other thermal springs appear to be distant from volcanic sources of heat and are probably associated with deep faults.

Many thermal and mineral springs carry enough mineral matter in solution to cause deposition around the outlet of the spring. The deposits may take the form of terraces, or mounds, or aprons on the down slope side of the spring. The terraces of the thermal springs and geysers of the Yellowstone are well known. Spring deposits are commonly composed of calcium carbonate (calcareous tufa) and silica (siliceous sinter); less commonly, iron oxides, sulfur,

and other minerals are deposited The waters of many thermal and mineral springs are reputed to have medicinal and therapeutic properties.

The flow of many springs varies considerably from time to time Wide fluctuation of discharge coincident with heavy rains, temporary turbidity, and marked variations in water temperature often signify a shallow source of the water. The utilization of the spring showing these indications, therefore, may be inadvisable for some purposes

*Wells.* The development of ground water—its extraction from the ground—is properly in the province of hydraulic engineering However, a brief and elementary approach to the subject is made here to establish a link between the geology of ground water and some engineering aspects of its development For any project, the choice of well type and method of excavation, probable yield, and the proper spacing of wells are problems whose solutions are more or less dependent on geologic conditions

Several varieties of wells are common The choice of type depends principally upon the nature of the material, the expected depth, and upon the expected life and output of the well In the following discussion, wells are classified according to the method of sinking them, as dug, bored, driven, jetted, hydraulic rotary drilled, and churn-drilled wells.

*Dug Wells.* The earliest wells were hand dug, and some of the early wells were dug to surprising depths. One method of putting them down was to suspend a slave by the heels and to encourage him to fill his bucket from the bottom of the hole Dug wells, cased with stone, brick, or other material, are found today supplying water in many rural parts of the United States Dug wells are practical only in unconsolidated material with high water table. Orange peel and clam shell buckets are used as well as hand digging tools The diameter of dug wells varies from about 3 feet to 30 feet or more. A casing is generally sunk coincident with deepening the hole.

*Driven Wells.* In unconsolidated material, wells can be developed by driving a pipe with a pointed and slotted end, *well point*

(Fig. 16-16), into the ground. The points are of small diameter, seldom greater than 3 inches, and the pump cylinder is attached directly to the pipe. The pump will not work, of course, unless the water table stands or rises to within approximately 25 feet of the

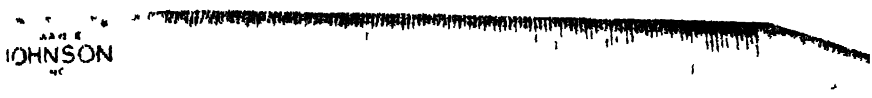



FIG 16 16 Well point (Courtesy of Edward E. Johnson, Inc.)

surface. Driven wells supply many houses, summer cottages, and small businesses with water; and batteries of driven wells serve many communities. Instead of driving the points, they may be jetted down. Driven wells are quickly put down, economical, and, where temporary supply is needed or small yield is satisfactory, are the usual type.

In many engineering projects, the dewatering of foundations is necessary for economical construction; for this purpose a system of driven wells is commonly used, as illustrated in Fig. 16-17.

A complication in this type of construction practice is illustrated by the experience of the New York City Housing Authority in a project for five 14-story apartment buildings of reinforced concrete. The water table had to be lowered 10 feet to permit construction of reinforced boxes for foundations. Adjacent structures, especially an adjacent 15-story hotel supported on spread footings, would have settled destructively by lowering of the water table beneath the footings Consequently, in this project, of the 4500 gallons per minute withdrawn through the well-point system established for the new construction, 3000 gallons per minute were fed back into the adjacent ground through a diffusion system of well points to maintain stability of the adjacent areas. By this means the normal water table level was maintained as close as 110 feet to the excavation.[5]

*Bored Wells.* Augers, hand or power driven, are used in unconsolidated material. In earth that will not stand, casing must be driven as the hole is augered. Wells of large diameter can be bored,

[5] *Eng News-Record*, Vol. 156, 1956, pp 39-42.

but the equipment necessary is so heavy as to limit its use. Bored wells are not so common as formerly, although much use of the auger is made in putting down small-diameter exploratory holes and for sampling sedimentary beds.

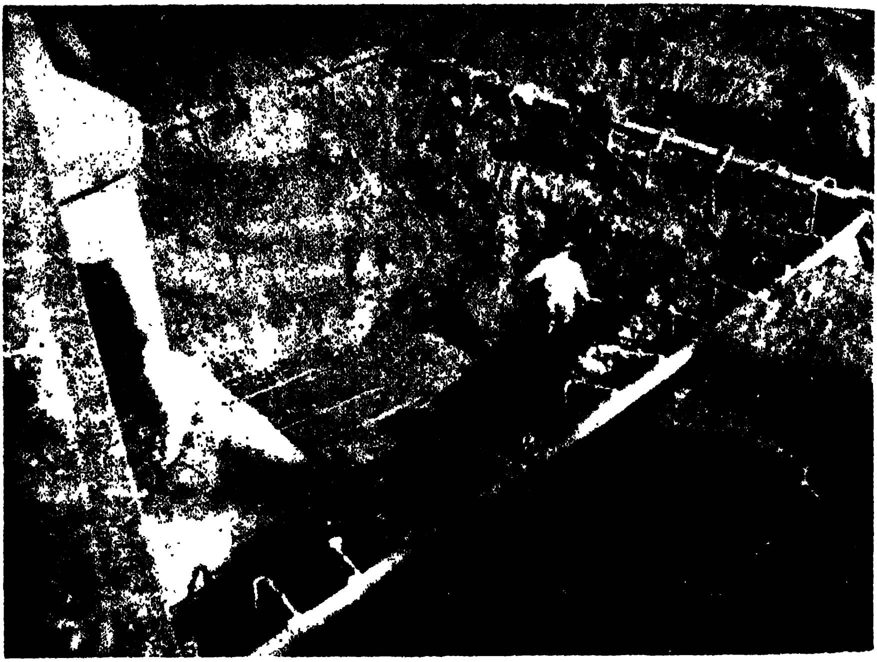


FIG. 16-17. Dewatering by well points. The upstream end of this bridge pier was to be protected by a V-shaped mass of concrete. The water in the river channel was about 10 feet above the bottom of the excavation, and only 6 feet away from the header. (Courtesy of Edward E. Johnson, Inc.)

*Jetted Wells.* Hollow drill rods down through which water can be pumped to a perforated point are much used and enable a hole to be sunk rapidly through unconsolidated material. The drill water is returned to the surface through an outside pipe (Fig. 16-18). Jet or wash boring is much used in sounding the depths to bedrock. Boulders or ledge, of course, limit the depth of either driven or jetted holes.

*Hydraulic Rotary-Drilled Wells.* Hydraulic rotary drilling is similar to boring in that a bit or cutting edge is rotated on the end

of a drill pipe Drilling mud is forced down inside the pipe and out through openings at the bottom, whence it rises outside the pipe, carrying the cuttings to the surface Hydraulic rotary drills can cut holes of large diameter and more readily permit gravel packing around a casing than the other methods This method is more satisfactory also than most other methods for the penetration of alternating soft and hard layers

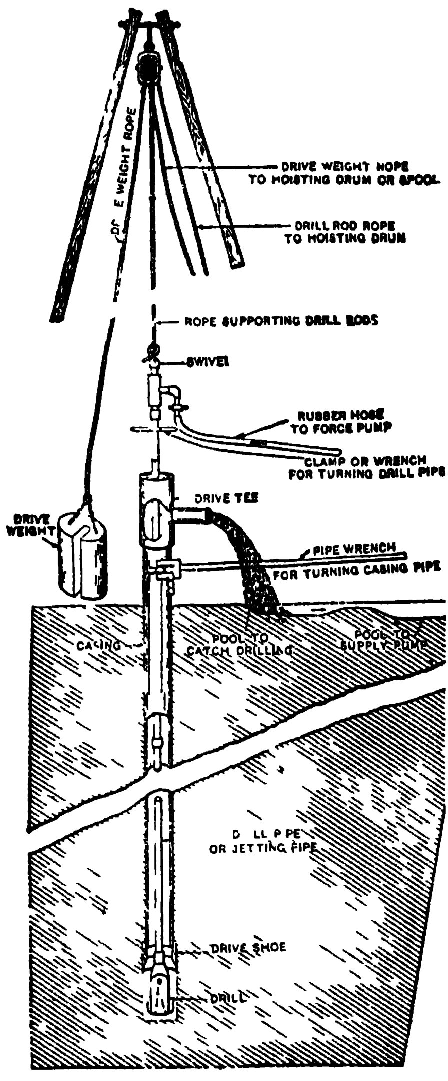



Fig 16 18 Simple jetting rig (Courtesy of Edward E Johnson Inc)

*Churn Drilled Wells* In churn drilling, also called the "standard" method, a string of tools is alternately lifted and dropped, "churned" up and down, to pound and cut a hole The string of tools consists of a bit and stem, a set of jars (linked steel rods to jar the bit loose if it gets stuck), a sinker bar to provide weight, and a rope socket which is designed to reduce jar on the drilling rig Fig 16 19 shows a string of standard drilling tools The cuttings are removed by various types of bailers or buckets Churn drilling is the most widely used method of putting down wells and is adapted to most types of rock

*Yield of Wells* The yield of wells depends primarily upon the character of the water bearing formation One of the most produc-

tive wells in the United States yields 25,000,000 gallons per day, a 24-inch well in Texas. The size of the well is distinctly of secondary importance. Table 16.2 illustrates the fallacy of the idea that big wells necessarily mean proportionately large yields.

TABLE 16.2.* APPROXIMATE INCREASE IN YIELD DUE TO INCREASE IN DIAMETER (SCREENS OF SAME LENGTH IN SAME FORMATION)

| Well Diameters | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2″ | 4″ | 6″ | 8″ | 12″ | 18″ | 24″ | 36″ |
| Increase in Per Cent | | | | | | | |
| 0 | 10 | 15 | 20 | 25 | 33 | 38 | 18 |
| | 0 | 5 | 10 | 15 | 23 | 28 | 38 |
| | | 0 | 5 | 10 | 18 | 23 | 33 |
| | | | 0 | 5 | 13 | 18 | 28 |
| | | | | 0 | 8 | 13 | 23 |
| | | | | | 0 | 5 | 15 |
| | | | | | | 0 | 10 |
| | | | | | | | 0 |

To obtain difference in yield between wells of various diameters: start at 0 in column for smaller diameter being considered, then move right into column for the larger diameter for comparison. If an 8″ well is being compared to a 12″ well, then 8″ is 0 and under 12″ the estimated increase in yield due to the increase in diameter is 5%. Figures are based on all conditions being identical except diameter.

* From Bennison.

Whenever water is pumped from a well, the water table is lowered around the well. The lowering is greatest at the well and diminishes away from it. In homogeneous material, with an initially level water table, this lowering is, therefore, of conical shape and is called the *cone of depression*. Frequently, the cone is elliptical rather than circular in cross section. With continued pumping, the lowering of the water level at the well steepens the hydraulic gradient about the well until the inflow and withdrawal balance. The cone of depression is illustrated in Fig. 16-19. The relation between draw down and yield of the formation has been expressed in a

variety of formulae. The relation of draw down to percentage relative yield is plotted as curves for both artesian and nonartesian water in Fig. 16-20. Referring to this figure, it will be seen that with a draw down of the static water level of 50 per cent (with reference to the bottom of the well) 76 per cent of the maximum yield is being pumped.

The slope of the water table established by pumping the well flattens out away from the well. The distance away from the well at

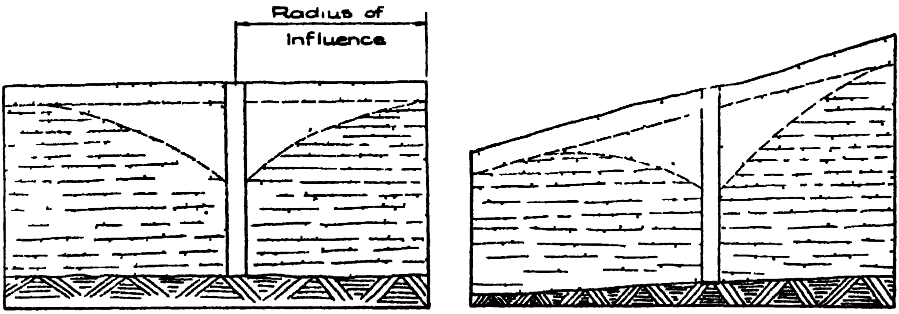



FIG. 16 19. Cone of depression caused by pumping.

which lowering of the water table caused by the pumping is not appreciable is called the *radius of influence*. The proper spacing of wells must take possible interferences into account. Bennison[6] gives an interesting example of well spacing:

"Eight wells were spaced 250 feet apart, in a line making about a forty-five degree angle with the direction of ground water flow. The total yield of the eight wells as located and operated was about 3,500 g.p.m. It was shown that by abandoning every other well and resetting the pumps, the pumping level was the same and yield was increased to at least 4,500 g.p.m., an increase of over twenty-eight per cent."

The radius of influence is largest and rate of recovery after pumping most rapid in coarse material. The less permeable the material

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[6] Bennison, E. W., *Ground Water, Its Development, Uses, and Conservation*, Ann Arbor, 1947, p. 215.

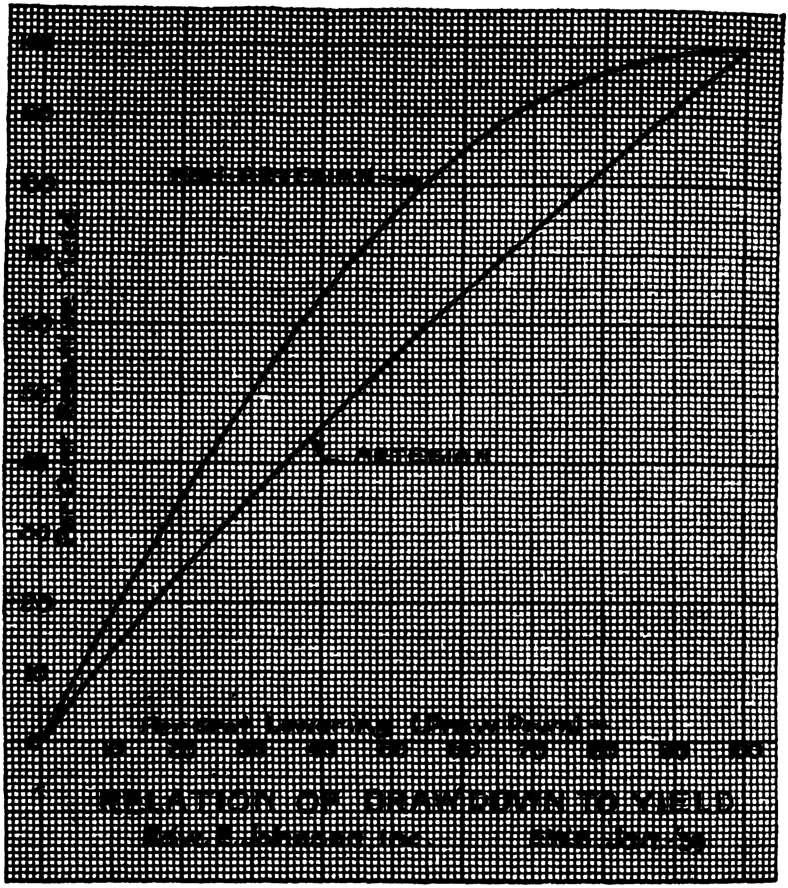

FIG. 16-20. Curve showing relation of draw down to yield. (Courtesy of Edward E. Johnson, Inc.)

the steeper is the cone of depression and the smaller is the radius of influence. Representative radii of influence (in feet) are:

| | |
|---|---|
| Silty sand | 100– 300 |
| Fine to medium sand | 300– 600 |
| Coarse sand and fine gravel | 600–1200 |
| Gravel | 1200–2400 |

The radius of influence can be determined from observation holes regularly spaced in a straight line from the well.

## Ground Water Recharge

With increasing demand for water, many industries or communities have drawn too heavily from the available supply. Obviously, intake must balance output over a period, or else depletion will result. Recharge of water-bearing formations can be aided by engineering effort. A formation that will yield water will take up water. A water table mound, the reverse of the cone of depression is formed where water is introduced, because in most soils the introduction of water is more rapid than lateral percolation. The water table must be deep enough below the surface, therefore, to give room for the water table to build up. As the hydraulic gradient about the intake is steepened by the mound, percolation into permeable surroundings is increased. Although variations of detail are introduced, the two methods of getting water into the ground are (1) by leading water over permeable surfaces, or water spreading and (2) by introducing water into "inverted" or recharge wells.

Surface water, from stream or reservoir, is diverted to spreading basins or diversion canals of permeable bottom where the bulk of it can leak into the gound. Water spreading has been effectively practiced in many places. Des Moines, Iowa, for example, has a very efficiently operated and effective system of ground water recharge through infiltration basins (Fig. 16-21).

The use of wells through which water may be fed into underground storage has also long been established practice. A recharge well is the opposite of an ordinary well: water is put in instead of being withdrawn. The recent increase in the use of air-conditioning systems which use cold ground water has taxed the ground water supply of many places. Water warmed in this use is locally being returned to the ground to alleviate serious lowerings of the water table. On Long Island, for example, the number of recharge wells has increased to number currently nearly four hundred, through which in the air-conditioning season over 12,000,000 gallons per day are returned to the ground. Another illustration is the recharge practice of

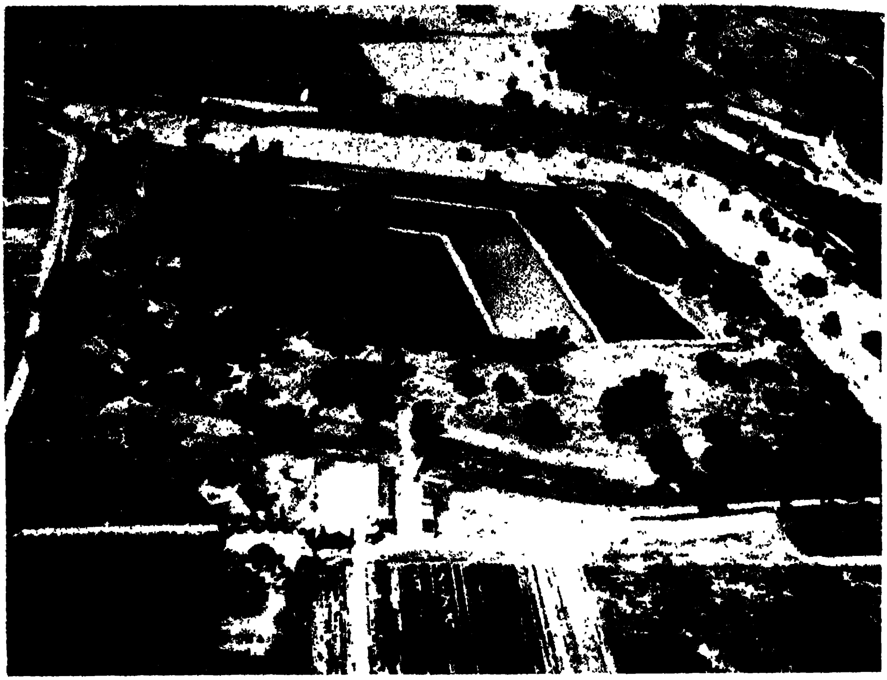

FIG. 16-21. Water spreading at Des Moines, Iowa. (Courtesy Dale L. Maffitt)

distilleries at Louisville, Kentucky.[7] This area experienced a serious shortage of cool water as a result of increased alcohol manufacture during the war. The supply previously had been from plant wells which in 1935 supplied 37,000,000 gallons of cold water per day. In 1943, the demand was for 62,000,000 gallons per day, and the water table was dangerously lowered. The problem of supply was partially met by using city water during the cold season, and at the same time introducing cold city water into the depleted wells. In the summer months the temperature of the city water rises as high as 85°F., too warm for use, and the replenished wells were again pumped.

Experimental data show that sodium-bearing water spread on a clay soil tends to deflocculate the clay and by ion exchange also tends to reduce the permeability. On the other hand, an application

[7] Guyton, W. F., "Artificial Recharge of Glacial Sand and Gravel with Filtered River Water at Louisville, Kentucky," *Econ. Geol.*, Vol. 41, 1946, pp. 644-658.

of calcium chloride or of gypsum ($CaSO_4 \cdot nH_2O$) tends to render a clay soil more permeable. As reported by Muckel,[8] this type of treatment of clay soils for water spreading has a beneficial but temporary effect in increasing permeability. Plowing and harrowing a soil over which water is to be spread are deleterious in the long run. A grass cover, however, improves the intake.

## Water Finding

Human settlements from the earliest known to the most recent have necessarily been where potable water could be obtained. With increases of population and rise of industry, demand for water has steadily mounted. Many individual pulp and paper plants, for example, require 20 to 30 million gallons a day. Agriculture also, spreading into dry regions, makes larger demands on water supply than formerly. Although the greater part of the required water is taken from surface sources, the volume drawn from the ground is huge. Accurate figures are not available, but at least 15 per cent and perhaps as much as 25 per cent of the population of the United States is dependent on ground water.

Use requires discovery—hence prospecting. Prospecting methods for subsurface water supply fall into four categories: (1) surface observation, or geological reconnaissance; (2) subsurface observation by means of test holes; (3) geophysical determination of subsurface conditions; and (4) superstitious hocus pocus.

Geological reconnaissance of an area often suffices to give an adequate concept of ground water conditions. If, for example, a terrain is relatively level, pockmarked with swampy areas and ponds, it is fairly certain that a high water table will be found; if the rock section, i.e., the sequence of layers in a sedimentary series can be observed or pieced together, the water-carrying members can be recognized; or if the joint or fracture pattern of crystalline rocks is studied, favorable spots for drilling may be located. In summary, familiarity with the water table-topographic relations and with the

[8] Muckel, Dean C., "Research in Water Spreading," *Trans. Am. Soc. Civil Engrs.*, Vol. 118, 1953, pp. 209-217.

porosity-permeability characteristics of various rock types enables an experienced observer to make shrewd deductions as to favorable sources of supply and probable depth to them. Many well drillers and others technically untrained in geological science have developed powers of keen observation and uncanny ability to size up a terrain for favorable well sites.

General or qualitative information, however, often does not suffice. Direct observations of the ground water level (and frequently of potential yield) are made by putting down observation holes. The majority of ground water developments for which test holes are put down are in unconsolidated rock; hence hydraulic rotary drills, jetting drills, and augurs are the usual rigs employed. Enough test holes should be made to ascertain the thickness, extent, and depth of water-bearing strata; one hole is frequently worse than none. In a well-planned program of testing, the direction of ground water flow is determined by relatively few tests. Further tests may well be located at right angles to that direction in order to find where the water-bearing layers are thickest and coarsest. Test holes, to be of highest value, should not only indicate the static level, but also the thickness and character of water-bearing strata. Hence, most test holes should be cased as made, auger-bucket or sand-bucket samples taken, and the hole logged. Samples of the strata penetrated should be individually bagged and properly labeled for laboratory analysis. Although expense prohibits extensive prospecting by test holes in consolidated rock, test holes are used and frequently developed into permanent wells. The volume of water required determines the amount of test holing justified. A five-hundred-dollar well, of course, does not ordinarily call for a thousand-dollar prospecting program.

Geophysical prospecting (see Chapter XII) for water at present is rather limited. In general, only electrical methods are of much practical value, and these chiefly in unconsolidated sediments. Some state agencies, notably the Illinois Geological Survey,[9] have used electrical methods with success. To interpret the results of electrical

[9] Bays, C. A., "Use of Geophysical Methods in Groundwater Supply," *Ill. Geol. Survey Circular 122*, 1946.

surveys requires considerable experience and familiarity with the characteristics of the types of materials present. To date, electrical prospecting is valuable only where considerable information on the local geology is at hand and where enough geophysical prospecting can be carried out to permit correlation of the results with the geology. The initial cost, maintenance, and operation of geophysical equipment are prohibitive for water work unless considerable prospecting is to be done. On a regional basis, for some types of underground, the method gives good results; limited to a particular job in a restricted area the method is costly, and results frequently unsatisfactory.

Superstitions about ground water still exist in the minds of many people. One of the better known of these fanciful delusions is the action of a forked stick in the hands of a "diviner." It is thought by many that some people either are endowed with a special sensitivity or have acquired a certain skill in the use of a divining rod which enables them to locate underground water. The practice of crotched-stick prospecting is variously called *dowsing*, *water witching*, or *divining*. Many well sites have been located by diviners; consequently, many people have faith in the method. The widespread occurrence of ground water accounts for the successes that have been credited to dowsing rather than any special gift or skill on the part of the dowser. In a humid region the chances for a moderately successful well are about nine out of ten wherever the well is put down. With these odds in his favor, a dowser's reputation depends largely on an uninhibited performance with the "groaning, twisting, writhing rod." In justice to some, however, it should be said that not all water witches are fakers. Some (self-hypnotized?) undoubtedly believe sincerely in their powers; others craftily practice the art.

## Frost

Frozen subsurface water is called *frost*. During every frost season many highways of the northern tier of states suffer frost damage. The bills for repair total several millions of dollars annually. In

addition, frost dislocates and breaks pipes, causes uneven uplift or settlement of many structures, and does other damage. In the high latitudes of both Eurasia and North America deep frosts that remain in the ground the year round present engineering problems of a type not met in warmer regions. The North Polar regions are increasingly strategic in world politics both because of air lanes which cross them and because of potential economic resources Engineering developments within these regions must cope with cold below the earth's surface as well as above it The Alcan Highway is only one example. Air bases, radar installations, and natural resource development present engineering problems beyond those of similar projects of more temperate latitudes.

The problems of frozen ground water, frost, can be met most successfully and economically if widely understood The phenomena of seasonally frozen ground have been known to engineers for many years, although imperfectly understood; the phenomena of permanently frozen ground have only recently been brought to the attention of engineers.

***Seasonal Frost.*** The problems of frost and cold ground are not confined to polar regions, as every mid-latitude engineer knows Destruction or impairment of pavements, disintegration of surfaces, frost boils, and sundry other effects of seasonal freezing have focused attention on seasonal frosts wherever they occur. Although valid estimates of the amounts of heave are few, heaves of more than 2 feet are well authenticated.

In Bristol, England, there is a four-story brick structure, 100 feet by 200 feet, occupied by a cold storage store. The working temperature of the cold chambers is 14° to 20°F. The structure is founded on 50 feet of soft silty clay, supported on reinforced concrete piles. The floor is independent of the main frame and laid on a 12-inch layer of ashes, two 3-inch layers of granulated cork and cement, and a 2-inch granulitic concrete wearing surface. Because of the continual low temperature, the floor slab heaved 25.5 inches, reduced the headroom from 8 feet 6 inches to 6 feet 4.5 inches, dam-

aged partition walls, jammed doors, cracked floor slabs, and made various inconveniences thereby.[10]

When water freezes, the volume expansion is approximately 10 per cent. Frost heave has often been explained, accordingly, as simply the expansion of soil water as it changes into ice. The thrust of frost heave has been stated to be predominantly upward because relief is easier upward than in any other direction. The work of Taber[11] has shown that neither of these concepts is correct. Other workers have substantiated Taber's general conclusions.

A brief consideration will indicate that frost heave is not satisfactorily explained solely by the expansion of freezing water. If a column of soil with a cross section of 1 square foot and a length of 10 feet, containing 50 per cent by volume of pore space completely saturated with water, is frozen throughout, its increase in length due to the expansion of the water into ice is slightly less than 6 inches, if all the volume increase goes into extension. In few regions of the United States does soil water freeze to average depths below the surface greater than 3 or 4 feet. For an extension of a foot and a half, therefore, this column would have to be 30 feet long. Even if the column considered was all water and no soil, its length would have to be 15 feet to extend a foot and a half on freezing. Evidently a freezing of soils to depths of 3 or 4 feet that causes heaves of several inches draws water into the freezing zone from the soil beneath.

Capillary action, strictly speaking, does not account for upward movement of soil water into the freezing zone, for there is no free surface or meniscus. Taber[12] ascribes the rise to the force of molecular or surface attraction acting in fine-textured soils to replace mo-

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[10] Sivewright, W. J., and Whittington, S. P., "Reconstruction of the Ground Floor of the Royal Edward Cold Store, Avenmouth Docks," *Proc. Inst. Civil Engrs.*, Pt. 3, 1954, pp. 166-182.

[11] Taber, Stephen, "Frost Heaving," *J. Geol.*, Vol. 37, 1929, pp. 428-461; "Mechanics of Frost Heaving," *J. Geol.*, Vol. 38, 1930, pp. 303-317; "Freezing and Thawing of Soils as Factors in the Destruction of Road Pavements," *Public Roads*, Vol. 11, 1930.

[12] *Ibid.*, p. 459.

lecules of water extracted by growing ice crystals from film or capillary moisture. Water, which has a surprising tensile strength, is drawn to the freezing zone and builds ice lenses.

Both field and laboratory observations show that frost heave invariably is accompanied by ice lenses (Figs. 16-22, 16-23). Indeed,

*Armco*

FIG. 16-22. Frost damage to pavement.

as closely as can be determined, the combined thickness of the ice lenses equals the amount of heave. Within the lenses, the ice crystals are oriented and grow in the direction of maximum heat conduction (normal to the cooling surface), and the direction of maximum thrust corresponds. Ice segregation and lensing take place when the freezing process can draw water to the freezing level. As the freezing isotherm drops deeper beneath the surface, new lenses develop with more or less rhythmical regularity at lower levels. Possibly alter-

nate freezing and thawing aid in segregation. The soil layer beneath the freezing zone is slightly warmer than the soil at the base of the freezing zone. Heat therefore flows upward, and some melting from the bottom up takes place during the warm spells The moisture

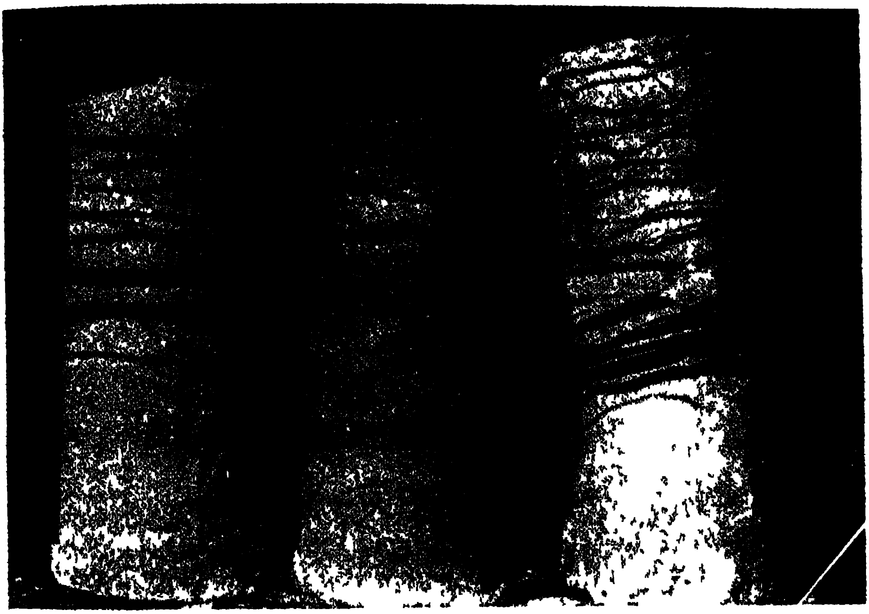

FIG 16 23 Ice lenses. (Courtesy of Stephen Taber)

drawn up into the freezing zone in the earlier cycle is thus available for further segregation into lenses when a drop in temperature again lowers the freezing isotherm

Growing ice crystals exert forces comparable to the crushing strength of the crystals under the conditions of growth. Mutual lateral support and confinement increase the crushing strength and make possible thrusts in excess of the crushing strength of unconfined ice crystals. Muller[18] states that stresses that develop in freezing ground may exceed 2000 kilograms per square centimeter.

Field observation shows that silty and clayey soils heave most. The particle size range of heaving soils, as determined by Beskow,

[18] Muller, S W, *Permafrost*, J. W. Edwards, Inc, 1947, p. 1.

is shown in Fig. 16-25. Casagrande reports that the critical diameter of particle size for heave is 0.02 mm. For a soil with less than 1 per cent of particles of 0.02 mm diameter or smaller, there is no heave; if more than 3 per cent of particles of 0.02 mm diameter or smaller are present, heaves are expected.

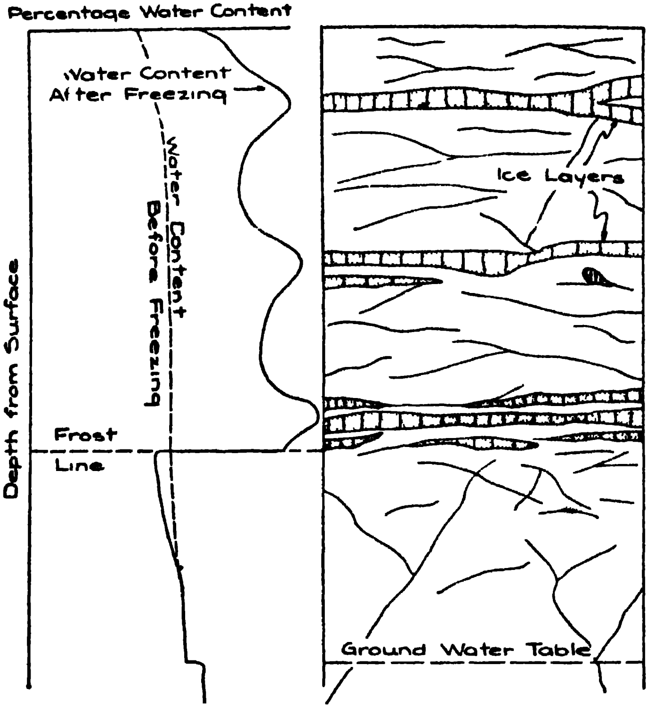


FIG. 16-24 Ice lenses and the change of water content in the soil due to freezing. (From J. O. Osterberg, *Civil Eng.*, Vol. 10, 1940)

Adequate drainage of subgrade soil, lowering of the water table, and the emplacement of coarse layers in position to drain freely and so to cut off the capillary-like rise of moisture during freezing are measures to reduce damage. Deep drains on the upslope side of the highway, as shown in Fig. 16-26, reduce heave although they do not, of course, remove capillary water. Complete or at least uniform removal of snow from highways, even from the shoulders if practical, reduces differential heaves of pavement. Replacement of heavable

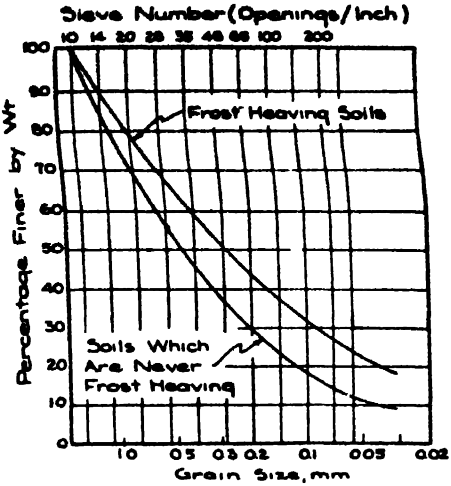


FIG. 16-25 Particle size range of heaving soils (After Beskow, from J O Osterberg, *Civil Engineering*, Vol 10, 1940)

soils with nonheavable material is an obvious remedy; although often economically impossible for an entire project, this method can be locally applied to prevent culvert damage or displacement. In some places, salt or another chemical has been used to lower the freezing point of soil water below expected temperatures; and locally, insulation, peat moss or cinders, for example, has been used.

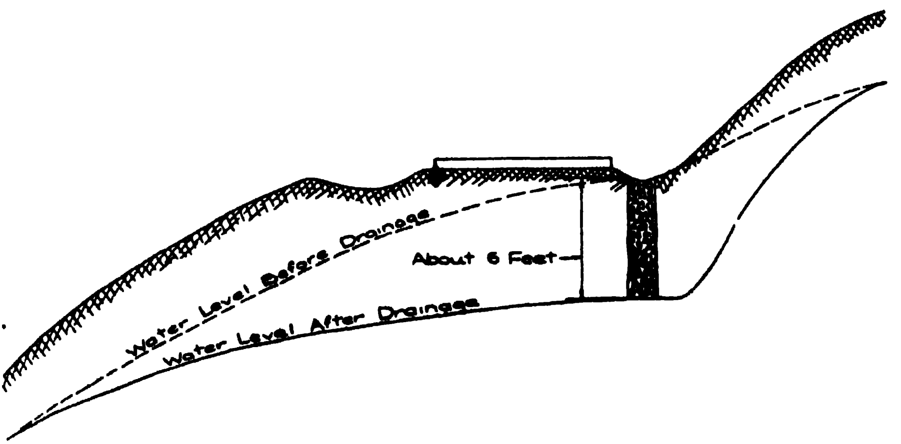


FIG. 16-26. Deep drains on upslope side of highway. (From J. O Osterberg, *Civil Eng.*, Vol. 10, 1940.)

***Permafrost.*** In North America permanently frozen ground, *permafrost,* is found widespread north of an irregular line which from approximately latitude 55° on the Labrador coast loops southward round Hudson Bay and swings northward again to approximately latitude 60° south of Great Slave Lake. Larger areas of Eurasia are permanently frozen than in North America; and Antarctica also has an extensive area of permafrost. All told, perhaps 20 per cent of the earth's land area is permanently frozen beneath the surface layers of the ground.

Permafrost extends downward to varying depths. In northern Greenland, rock a thousand feet below the surface was found to have a temperature below freezing; freezing temperatures there probably extend to a depth of at least 1500 feet below the surface.

Both distribution and depth suggest that permafrost is in part a holdover from the recent glacial epoch, as do also some perfectly preserved remains of the long extinct woolly elephant, whose meat has been so well preserved in cold storage as to still be edible. Above the perennially frozen layers is the so-called *active zone* in which the ground thaws during the summer months. The active zone, in the melting season, is often a water-logged soil, for downward drainage is inhibited by the permafrost and much of the topography of the permafrost regions is without strong relief. The thickness of the active zone varies with latitude, soil type, exposure, vegetation, and other factors. In Siberia, where permafrost investigations have been

TABLE 16.3.* THICKNESS OF SEASONALLY MELTED ZONE ABOVE PERMAFROST, SIBERIA

| Location | Sandy Ground | Clayey Ground | Peaty and Swampy Ground |
|---|---|---|---|
| South of Lat. 55° N. | 3–4 m | 1.8–2.5 m | 0.7–1 m |
| Lat. 62° N. | 2–2.5 m | 1.5–2 m | 0.5 m + |
| Arctic Coast | 1.2–1.6 m | 0.1–1 m | 0.2–0.1 m |

* Muller, S. W., *op. cit.*, p. 9.

most detailed, depth measurements have been made, the results of which are shown in Table 16.3.

When the surface of the ground freezes, the water between the frost table (top of permafrost) and frozen surface layers is confined and may be under hydrostatic head. If pressure is great enough, the water may break out at the surface as artesian springs, from which spread ice sheets called *icings*. If they occur along a highway or air strip, icings may completely dislocate traffic. They also cause serious damage to other structures. Freezing below the surface makes ground ice which locally causes excessive heave. Swellings, or mounds due to freezing water under pressure within the active zone, may bulge upward as much as 300 feet, and the swelling may be lateral as well as upward. Peaty, clayey, and silty soils are the types most subject to swelling. Melting of ground ice or irregular melting of the permafrost forms depressions and uneven surfaces. Saturated surficial soils of the active zone are subject to flow (solifluction) on low slopes.

Engineering measures to meet the unusual conditions imposed by permafrost are still in the experimental stages. Use of insulation to prevent melting of the permafrost under or adjacent to a structure, for example wide highway berms, provision for drainage of the active layer if feasible, anchoring structures within the permafrost, and replacement of swelling material with nonswelling sand or gravel are general ways of minimizing damage. The interested engineer will find much useful and valuable data and many helpful hints and cautions for construction in Muller's book.

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CHAPTER XVII

# EARTH MOVEMENTS

EARTH MOVEMENTS INCLUDE BOTH THE SPECTACULAR slips of material which receive wide publicity and the all but imperceptible creep which receives scant notice. Catastrophic avalanches or rock falls, which may translocate tens of millions of tons of earth material in a matter of minutes, have taken an uncounted toll in life and property. Still greater monetary losses, however, have been caused by the less spectacular earth failures. In an area, for example, embracing parts of western Pennsylvania, southern and eastern Kentucky, western West Virginia, and southern and eastern Ohio, slope failures cause an annual highway repair and maintenance bill of more than $10,000,000.[1] The difficulties in the construction of the Panama Canal caused by slides are well known. A single rock slide at Niagara Falls, New York, in 1955 destroyed a power plant, with a replacement loss estimated at $100,000,000. In the United States, the problem of slide control has also been brought sharply into focus by the failure or partial failure of several great earth dams, although engineers have been combating slides for years.

When excavation is undertaken, fills made, or structures built, the engineer in charge assumes responsibility for the prevention or control of any earth movements which may result. Problems of design and of construction methods must take into account possible earth movement. Frequently, failures have necessitated redesign or reconstruction. Because problems of anticipation and prevention or of cure and control are so commonly met in both large- and small-scale construction, the subject of earth movements is of particular interest to the civil engineer.

[1] Ladd, G. E., "Landslides, Subsidences, and Rockfalls," *American Railway Engineering Association Proceedings,* Vol. 36, 1935, p. 1093.

## Classification of Earth Movements

Various classifications of earth movements have been presented Some have been based on the type of material involved; some have been based on the rate of movement; and others have been based on the kind of movement. The discussion which follows is based on the classification: [2]

A. Earth Flows
   Solifluction
   Creep
   Rapid Flows
B. Landslides
   Debris Slides and Slump
   Rock Slides
   Rock Falls
C. Subsidence
   Plastic Outflows
   Compaction
   Collapse

This classification is based on the distinction between flowage and failure on definite shearing surfaces; also recognized in the scheme are rates of movement and, to some extent, the types of material involved. *Earth flowage,* as used here, implies movements distributed through the mass. *Slides* are bulk movements limited to more or less definite surfaces or restricted zones. The distinction between these two primary types is shown in Fig. 17-1. Both types of movements, of course, may be present in any of the divisions. Earth movements grade from the transportation of unconsolidated debris by water or ice to essentially anhydrous movements of rock masses. In *subsidence,* the movement is dominantly downward.

***Earth Flows.*** Earth flows are characteristically composed of fine-textured sediment. A high water content and a state of open packing favor this type of failure. In the clays a dense state of packing is never achieved and flowage failures are particularly common. Al-

[2] Sharpe, C. F. S., *"Landslides and Related Phenomena,"* Columbia University Press, New York, 1938.

though clays often have a "set" and may fail initially in shear, once this set has been destroyed the movement generally becomes a flow. A condition of open packing such that deformation without increase of volume is permitted together with high water content enables coarser textured sediments also to flow. In clastic materials, if the state of packing is such as to require volume increase on deforma-

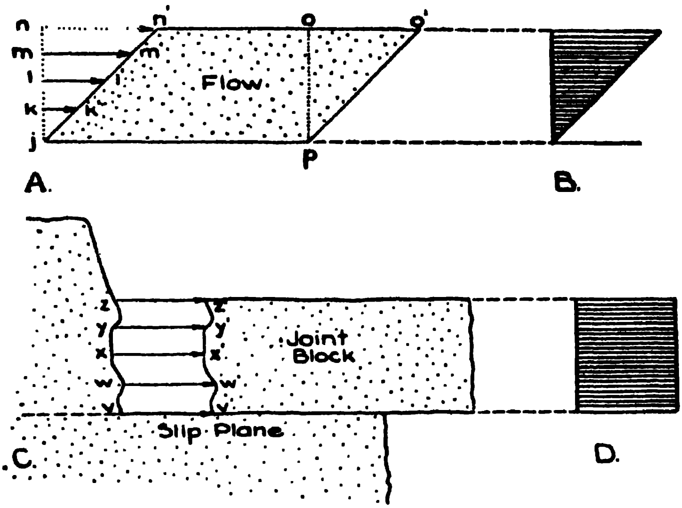


FIG. 17-1. Flow and slide movements. (Reproduced by permission from C. F. S. Sharpe, *Landslides and Related Phenomena*, Columbia University Press)

tion, failure along definite shearing surfaces commonly results because of the rigidity imparted to the mass by the weight of the overlying material. Movements that are initiated as slides, however, often become more plastic because of the change in state of packing during the translocation. Solifluction, creep, and rapid earth flows are movements of the flow type.

*Solifluction.* The term *solifluction* is applied to the slow downslope movement of wet, soupy soils under the action of gravity. Solifluction is particularly characteristic of the high latitude regions of permafrost. Because of the frozen subsoil condition, the surface layers become water soaked in the summer months, and in this

saturated condition flow gradually downgrade even on gentle slopes. In the frost zones of the middle latitudes, the failure of some pavements because of the excess moisture drawn up by frost action into the soil beneath the pavement illustrates solifluction on a small scale.

*Creep.* On many slopes the surficial material is in transit downgrade at an extremely slow rate. This type of movement is called *creep.* As used here, the distinction between creep and solifluction is the water content of the soil. Creep may be essentially anhydrous; in solifluction excess water is always present. Creep is particularly important to the engineer because the rate of movement is so slow that it may not be detected until its effects on engineering structures call attention to it. Thus railway tracks, highways, retaining walls, or tunnels built in or on creeping slopes may be thrown out of line or destroyed.

Creep can usually be recognized, however, by careful observation. The bending of rock strata downslope, dislodgment of fence posts or telephone poles, sag of tombstones, curvature of tree trunks, turf rolls in front of boulders, bulged or broken retaining walls, and effects on other structures are evidences of creep that have been noted by Sharpe and others; these are summarized in Fig. 17-2.

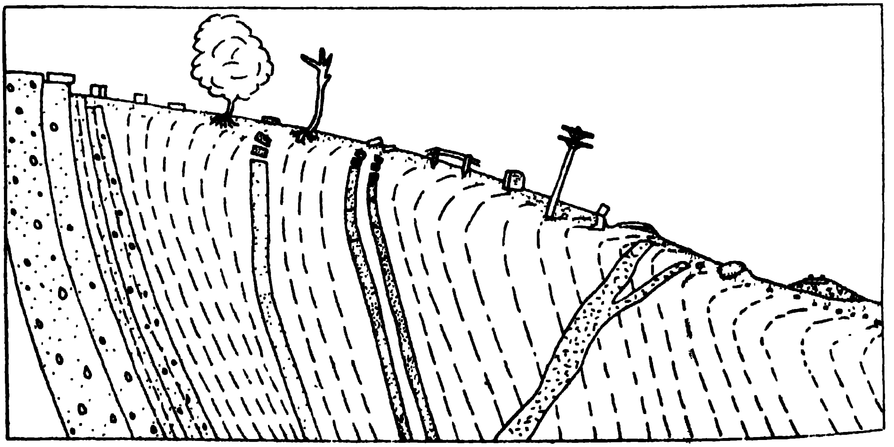

FIG. 17-2. Evidence of creep. (Reproduced by permission from C. F. S. Sharpe, *Landslides and Related Phenomena,* Columbia University Press)

The causes of creep are many. One of the principal causes is the action of frost. Ice crystals, which in growth develop surprising force, lift soil particles or even boulders in a direction normal to the slope. Melting permits slump and gravity pulls the lifted object down slope. The freezing of water in soil cracks also aids in down-slope movement. Many other causes contribute to creep, however, for the process takes place in all climates, and even under the surface mat of vegetation. Surface run-off or subsurface seep moves particles down slope, even if imperceptibly. Every opening in the soil, whether made by ant, angleworm, or other animal, or plant root, or by desiccation, is closed from the uphill side. Needless to say, the presence of water in the creeping material aids in the process.

*Rapid Flows.* Rapid flows differ from creep both in speed and in depth of substance involved. Whereas creep is essentially restricted to the surface or near it, rapid earth flows involve greater depth. Rapid earth flows differ from solifluction in rate of movement.

Various grades of material are subject to rapid flow. However, the finer textured soils, clay and silty clay, or the coarser textured soils with a relatively high clay content are the most common types in these flows, and the bulk of rapid earth flows are of wet clay. Once movement is started, wet clay becomes very plastic and flows readily on very gentle slopes. Most flows are associated with heavy rains or melting snows. The presence of permeable layers, silt or sand, interstratified with clay is a favoring condition, for water confined in the system in these layers may not find ready escape. Shrinkage cracks on clayey surfaces also permit ingress of water.

One of the best examples of these flows has been described by Sharpe [8] and others. This flow took place near St. Thuribe, Quebec. Here the river bank, 25 to 35 feet high, gave way during heavy rain, and some 3,500,000 cubic yards of clay and sand flowed out through a 200-foot opening into the Rivière Blanche, leaving an area 1700 feet by 3000 feet excavated to a depth of 15 to 30 feet. Sharpe's

[8] *Ibid.*, pp. 51-52.

diagram, Fig. 17-3, drawn from maps and photographs, illustrates the flow very clearly.

*Mudflows*, common in semiarid regions of sporadic heavy showers and scant vegetation, are similar to the earth flows of humid regions just described, although they are commonly confined to channels or old stream courses. Mudflows carry along boulders and other coarse

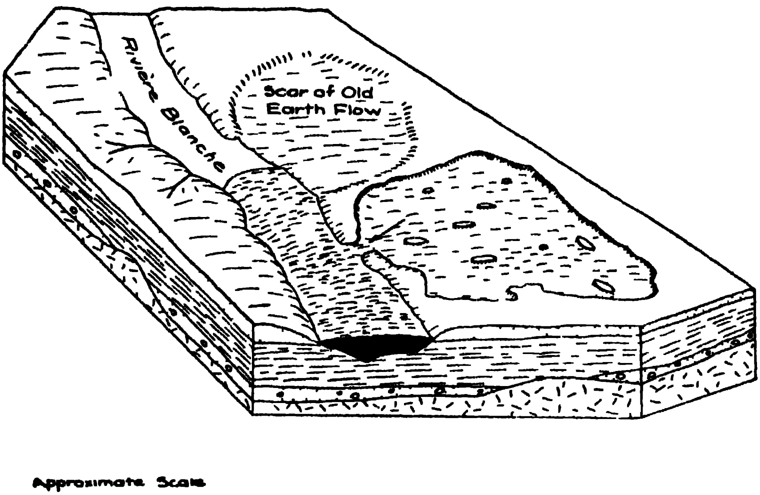


FIG. 17-3. Flow at St Thuribe (Reproduced by permission from C F S Sharpe, *Landslides and Related Phenomena*, Columbia University Press)

material as well, and the deposits are jumbled, unstratified masses which resemble those made directly by glacial ice. Mudflows have destroyed buildings, disrupted traffic lines, and ruined arable land at many places in semiarid regions. Deposits of fine ash or tuff from active or recently active volcanoes are also particularly susceptible to flow when saturated. Earthquake shocks associated with volcanism may start the flow. In part at least, the destruction of Herculaneum and Pompeii was by volcanic mudflow.

Flow failures in soils may be classified as in Table 17.1.

***Landslides.*** If a mass of earth or rock moves along a definite zone or surface, the failure is called a *landslide*. Debris slides, rock slides, and rock falls are the principal landslide types.

*Debris Slides and Slump.* Failures of unconsolidated material

TABLE 17.1.* FLOW SLIDES IN SOILS

| Sensitivity to Liquefaction | Soils Affected | Character of Strain | Character and Speed of Flow | Examples |
|---|---|---|---|---|
| High sensitivity | Sand in bulked condition; rock flour. | Small strains, earthquake shock, explosions, vibrations affecting large mass | Rapid flow; few minutes. | Silt flows in Laurentian Mts. |
| Low sensitivity | River sands; rock flour. | Large strains created simultaneously in a large volume, e.g., shear failure in clay transmitted into overlying sand | Rapid flow; few minutes. | Ft. Peck Dam; river sands in foundation, hydraulic fill sand in dam. |
| Low sensitivity | River sands; rock flour; varved silts and clays; clays having great sensitivity to remolding | Large strains created progressively. | Progressive liquifaction; up to several hours duration depending on mass involved. | Mississippi river bank slides. |

* After A. Casagrande.

on a surface or limited zone of rupture are called *debris slides.* A great many, perhaps most, debris slides are in part flow failures also, inasmuch as interparticle readjustments constitute flow. Earth flows and debris slides are distinguished, therefore, by the dominance either of flow or shear failure. The majority of debris slides are readjustments of slope; hence they are particularly abundant—and troublesome—accompanying or following engineering excavation that either oversteepens a slope or removes support of debris resting on a slope.

The construction of fills, likewise, is often attended by or followed by slides. Natural debris slides are numerous along river, lake, or sea margins subject to oversteepening; they happen on any slope where the internal resistance to shear is reduced below the safe limit by a change in the state of packing or of moisture content, or where load increases, by slide or creep from above or by rain-

or snowfall, exceed the strength of the soil. A debris slide on a steep slope that travels at a high speed is often called an *avalanche*.

*Slump*. The term *slump* is applied to debris slides, generally of small magnitude, that show some degree of backward rotation accompanying the downward displacement; slump is shown in Fig 17-4. Slump is often accompanied by complementary bulges at the

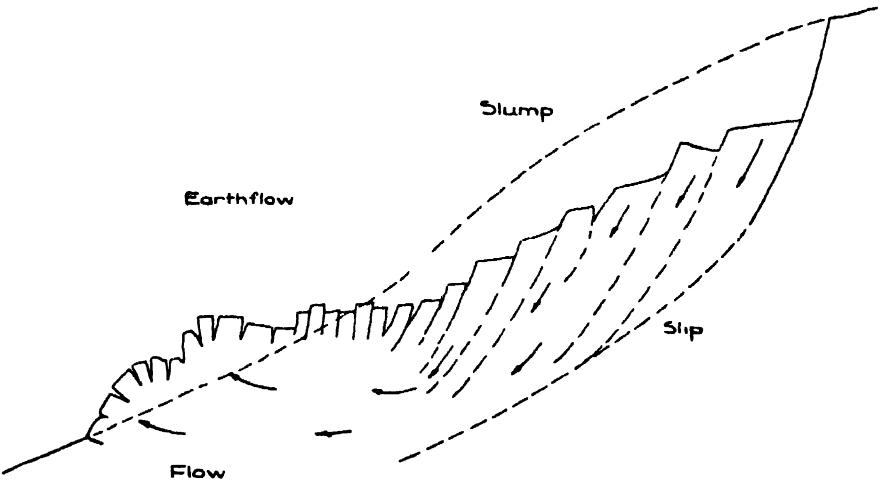


FIG. 17-4. Slump (Reproduced by permission from C F S Sharpe *Landslides and Related Phenomena*, Columbia University Press)

toe. Slumps are particularly common along cuts and fills and on natural slopes that have been cleared. The little terraces called "cat steps" or "cow paths" that are so common in hill pastures of the northern states are minor slumps.

Many engineers consider the surfaces on which slumps move to be cylindrical. This concept is a convention for simplifying mathematical analysis that is probably justified, considering the other assumptions that are necessary for mathematical treatment.

Noncohesive soils, when dry, have characteristic angles of repose. This angle varies according to the shapes and grading of the constituents and the density of packing; it is independent of the height of slope. Shear failure occurs when the shearing stress exceeds the

shearing resistance of the material. This is expressed by Coulomb's equation:

$$s = p \tan \phi$$

or for saturated ground:

$$s = (p - hw) \tan \phi$$

where $s$ is the shearing resistance per unit area, $p$ is the normal compressive stress, $h$ is the piezometric head, $w$ the unit weight of water, and $\phi$ the angle of shearing resistance, or angle of internal friction. Wet sand may stand with a steeper angle of repose than dry sand because of the cohesive effect of the moisture. If, however, more water is present than enough to merely fill the voids, the water carries a part of the stress, and both the coefficient of internal friction and the angle of repose are lowered. An extreme example is a quicksand that has no shearing strength.

To clarify and explain a little more fully these effects, a brief consideration of pressures in granular masses may be introduced. Consider a vertical cylindrical unit of homogeneous dry sand. The top surface of the soil cylinder coincides with the level surface of the deposit, and at depth $h$, the parallel bottom surface has an area $A$. The mass of sand thus inclosed is equal to the bulk density of the sand times volume:

$$W_s = \gamma_m A h$$

The mass $W_s$ must be wholly supported by the vertical component of the reaction on the bottom plane surface of the considered cylinder. The load is transmitted, of course, only from grain to grain. Other than the weight of the sand, there is no load (except air) on the lower bounding surface. This stress, $W_s/A$, is called the *effective stress* and may be symbolized $p_s$.

Consider now the same cylindrical unit fully saturated with water. It is only that part of a grain in contact with another grain that transmits pressure directly from particle to particle, whereas except at surfaces of interparticle contact the grains are subject to hydrostatic pressures. Part of the total pressure is thus transmitted to the

lower bounding surface as contact stress, and a part by hydrostatic pressure. Intergranular stress is reduced by buoyancy of the solid particles which is nearly equal to $\gamma_w[Ah/(1+e)]$ where $\gamma_w$ is the density of the water, $A$ is the area of the basal surface, and $e$ is the void ratio. The water pressure, $p_w$, is equal to $\gamma_w h$. The intergranular pressures, called the *effective stress*, are transmitted from grain to grain to the lower cylinder surface approximately equal the weight of the solid:

$$p_s = \gamma_w h \frac{G-1}{1+e}$$

The hydrostatic pressure on the lower surface is called the *neutral* or *pore water pressure* because it does not tend to affect the condition of packing or properties of the granular aggregate.

The total pressure $p$ is thus equal to the sum of the pore water pressure and effective stress:

$$p = p_w + p_s \quad \text{or} \quad p_s = p - p_w$$

and the effective stress diminishes with an increase of pore water pressure; that is, if the neutral stress increases or decreases the effective normal stress $p_s$ changes by the same amount. The shearing resistance of cohesionless soils therefore is expressed as

$$s = (p - p_w) \tan \phi$$

Thus the contributing effects of changing hydrostatic heads through increased (or decreased) pore water pressures are readily apparent. A simple application is shown by Fig 17-5. In the foregoing, the water has been considered essentially static. If, however, the pore water is in motion, it tends to drag along unconsolidated particles by frictional forces on the grains. Thus a downward percolation tends to increase the effective stresses, and an upward motion decreases them. Especially significant may be effects that lift the grains into an open-packed and hence less stable state, with increased permeability. A sudden drop in head, as by a rapid decrease of adjacent stream level at the end of a flood period, may also cause damaging bank failures.

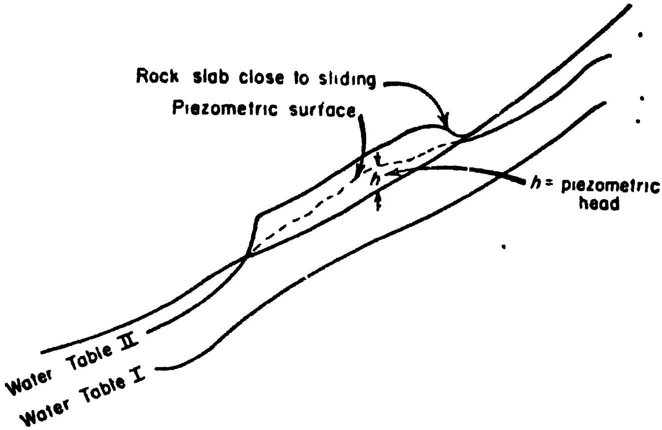


FIG. 17 5 Rise of the water table may cause the slide of a slab owing to an increase in pore water pressure (After Terzaghi)

For cohesive soils—clay, for example—the corresponding equation is

$$s = c + (p - hw) \tan \phi$$

where $c$ is the cohesion A change in the state of stress requires a change in the water content of a saturated soil. The rate of stress application is therefore important in stability considerations, for unless the water can escape freely to keep pace with the changed stress condition, stress is not entirely transmitted from particle to particle. Cohesive soils have low permeability The angle of shearing resistance for clays is seldom more than 20°, and for most clays is less than 15° Cohesive soils have no single angle of repose, for the angle at which a homogeneous cohesive mass will stand changes with the increase of slope height.

In the preceding discussion, the effect of water in a detrital mass has been indicated. If a debris slide takes place, the equilibrium which existed prior to the slide has been disturbed by a drop of shearing resistance, removal of support, change in loading, or some combination of these three factors Water entering the mass not only lowers shearing resistance, i e , reduces the coefficient of friction ($\tan \phi$ = coefficient of friction) but also adds weight to the mass. Any

escape of water from the debris, for example drainage, increases stability; any water kept from entering the mass conserves to that extent existing strength. A stomach pump may relieve an overstuffed child, the sensible parent prevents overstuffing.

*Rock Slides.* Movements of essentially consolidated material which consist chiefly of recently detached bedrock are called *rock*

FIG. 17-6 The dip of the beds at the right so closely approximates the slope of the hill that a heavy rain may precipitate the whole mass into the valley (After Fox)

*slides* Structures favorable to rock slides are outwardly inclined joints, fault surfaces, and weak or slippery strata (Fig. 17-6); removal of support from the downdip, downslope side either starts the slide or prepares the way for it. In the construction of highways, excavation on dip slopes has occasioned many slides. Better engineering practice on dip slopes where slides are probable may be to fill rather than cut in grading the route.

A notable rock slide took place at Frank, Alberta, in 1903.[4] An estimated thirty-five to forty million cubic yards of rock slid down the mountainside, overriding the town and killing seventy people. The slide pushed 400 feet up the opposite valley wall. Geologically, Turtle Mountain consists of limestone thrust over shale-sandstone beds (Fig. 17-7). The presence of joints dipping approximately 40° down the mountain slope weakened the rock mass, and earthquake vibrations previous to the slip had probably loosened the material and prepared the way for the catastrophe. The slide itself was probably set off by the heavy rains and frost immediately preceding.

*Rock Falls.* Blocks of rock of varying sizes may suddenly crash downward from steep slopes; many highways have signs warning of the danger of falling rocks. Large masses of rock may suddenly become detached from cliffs. Rock falls are common along steep shorelines and in the higher mountain regions. Spring and fall are the seasons of most danger.

***Subsidence.*** *Subsidence* is an essentially downward movement of the surface. Earth subsidence is due to both artificial and natural causes. In construction work, the engineer must frequently allow for subsidence and design accordingly. The mining engineer, also, must consider the possibility of surface subsidence as a result of his excavations. Much property damage has resulted from failure to anticipate subsidence. Subsidence is due largely to plastic outflow of underlying strata, to compaction of underlying material, or to collapse.

*Subsidence Due to Plastic Outflow.* Beneath heavy loads, plastic layers, or layers which become plastic due to disturbance as explained on page 100, may squeeze outward, allowing surface settlement or subsidence. Thus clay may be extruded from beneath a structure; or sand and silt layers, unless drainage is provided, locally may become plastic and flow. Many highway fills across soft ground have settled detrimentally, often with corresponding bulges at the sides of the fill.

*Subsidence Due to Compaction.* Sediments often compact be-

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[4] Daly, R. A., Miller, W. G., and Rice, G. S., "Report of the Commission Appointed to Investigate Turtle Mountain, Frank, Alberta," *Canada Geol. Survey Memoir 27*, 1912.

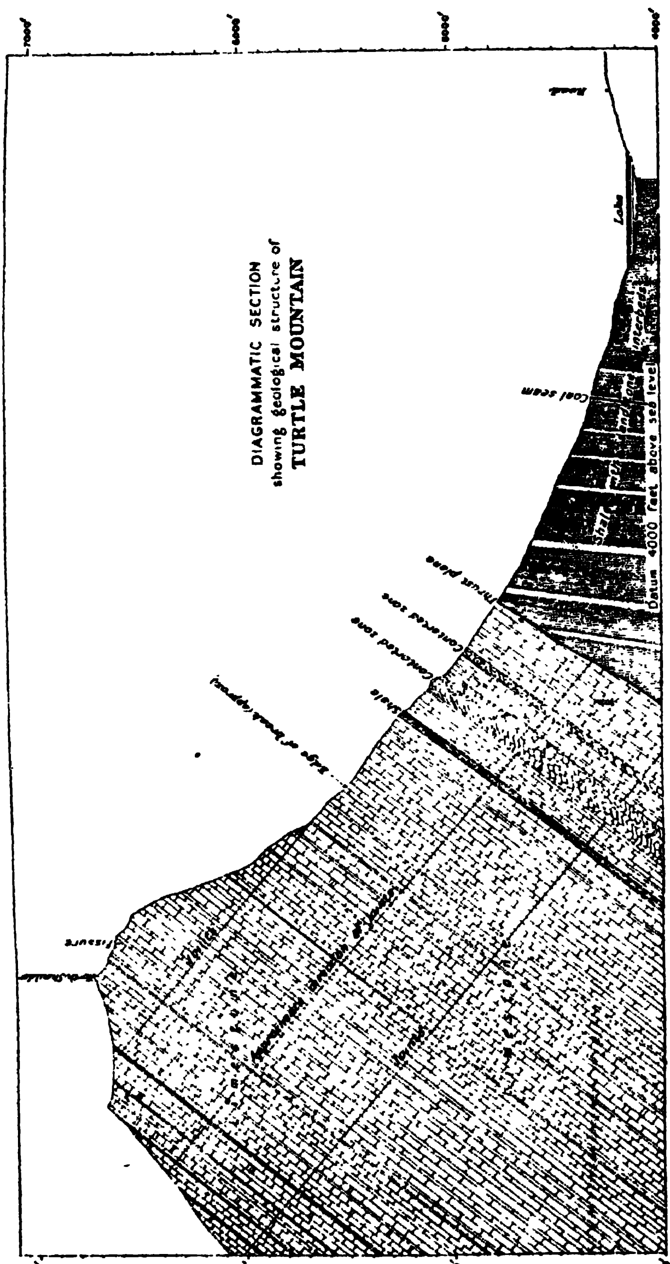



FIG. 17.7. Diagrammatic section showing geological structure of Turtle Mountain, Frank, Alberta. (Canadian Geological Survey)

cause of load or disturbance. Unless the water contained in the sediment can escape, an unstable hydrodynamic condition may be established by the compaction. Vibration is far the most effective means of compacting granular materials if the contained water can escape. Compression under load without vibration or disturbance is relatively ineffective in compacting granular material from the silt size up. Compaction is much more rapid in permeable sediments than in clays. The compaction or "consolidation" of clay may continue for years after a structure on it has been completed. Fortunately through the techniques of Soils Mechanics it is possible to approximate the amount and rate of clay compaction under load.

Excessive pumping of water and the withdrawal of oil from the ground has locally caused subsidence. An interesting legal point of land ownership arose because of a local subsidence on the Texas coast due to oil extraction. The land sank below sea level and was flooded; hence the government had a claim on the property; for unless alienated by special legislation, land below mean high tide belongs to the people.

*Subsidence Due to Collapse.* In regions where extensive underground mining has removed a large volume of material, the weight of overlying rock may cause collapse and subsidence. This type of subsidence has been particularly expensive in some of the coal regions where large areas are underlain by nearly horizontal coal beds. Many surface structures have been damaged, and many lawsuits fought through the courts as a result. Other types of mining, for example extraction of salt by solution, have caused subsidence.

Subsurface water leaches and dissolves away the more soluble rock types; collapse structures due to this cause have already been described. At least one public building has imposed an excess load on the roof of an unsuspected cavern beneath the structure; shoring to halt the subsidence was required.

*Large-Scale Subsidence.* On a grander scale than the preceding subsidence types are those that have affected large areas of the lands in the geologic past. The continents have frequently been flooded over very large areas. Causes for the downward movement of the

lands relative to the sea level are not understood. Overloading by sediments may cause local subsidence. The formation of Reelfoot Lake, Tennessee, in 1812, may have been caused by sedimentary overload. In volcanic regions, subsidence, presumably due to subsurface migration of liquid rock, has frequently taken place. The sinking of Port Royal in Jamaica is a subsidence in historic times that is ascribed to volcanic activity in nearby regions. The advance of the great ice sheets of recent geological time probably depressed the land. The major causes for great crustal movements, however, are unknown.

### Prevention and Control

Gravity is the primary cause of all flows and slides; only the authors of "wonder fiction" suspend its operation. In the preceding discussion of flows and slides the conditions favoring movement have been given. A summary of these may be convenient in considering prevention and control measures.

Water is the principal villain in the act of promoting slides and flows. Water may reduce cohesion; it adds weight. If present in excess, it imparts a hydrodynamic quality to the mass by carrying part of the stress. By freezing it exerts an expansive force. As snow it not only adds weight and melt water, but it may by its sliding induce sliding in underlying material: by shifting load, by friction, and by impact.

A clay content undoubtedly makes a mass more slippery and, when wet, promotes flow. A clay or shale layer is often the surface on which slides occur. If sufficiently wet and open-packed, however, coarse materials also will flow; and joints, faults, and bedding planes may be slip surfaces.

Disturbance of existing equilibrium by loading or by support removal is the proximate cause of movement. Increased loads and oversteepened slopes are due to both human and natural agents.

***Prevention.*** Wherever practical, deep cuts at the toe of an unconsolidated slope should be avoided. Because they are near the angle of repose, talus slopes are dangerous to disturb. Observation

of existing slopes and materials in the vicinity that are stable will show what may be expected The recognition of past instability, by slide and flow scars and by the hummocky topography of past slides and flows (Fig 17-8), helps the topographic analysis If slopes of 25°

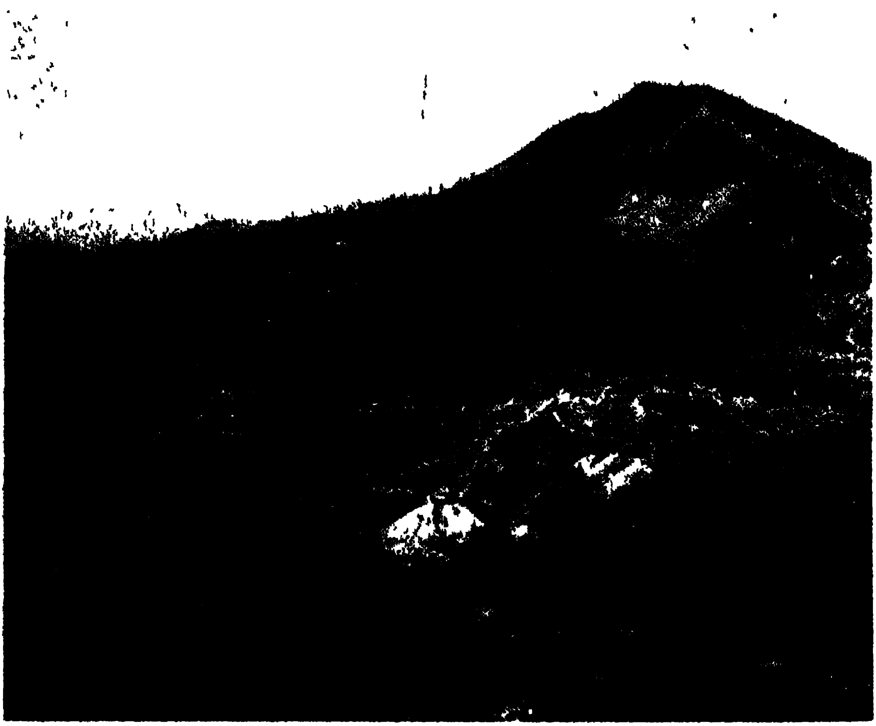
FIG 17 8 Landslide topography "Excavate! And watch the break move uphill It can go half a mile perhaps a mile (Photo by George Ladd)

have failed, as shown by topography, slopes approaching that angle or greater on similar material can be expected to give trouble

It is always cheaper to install proper drainage during construction than afterwards Diversion of water from a mass where potential movement is judged present is a safety measure Other methods of sealing off water entry have been successfully used, although frequently not until failures have required attention

Cuts in consolidated rock should be preceded by examination for structures, such as joints or other planes of weakness, that dip toward the cut. Grouting jointed rock above the cut has been found effective both to increase strength and to exclude water

Temporary measures to prevent slides and earth flows during construction include dewatering by well points about the excavation, freezing, grouting, and impregnation with sodium silicate or similar agents.



U. S. Geol

Fig. 17 9. Landslide topography.

***Remedial Measures.*** The thousands of slides and the many diverse situations in which they have happened necessarily have resulted in many different methods of treatment. Successful variations and combinations of method have been described in numerous articles in the literature of civil engineering. From the experience of many engineers, a few general principles and types of widely applicable controls have evolved. The principal methods are removal of slide material (excavation), slope treatment, retaining structures, and, most important, drainage.

*Excavation.* Perhaps the first thought when a slide has occurred, especially if it blocks traffic along a transportation route, is to put in a shovel and clean up the mess. For slides or flows of small background this clean-up method is practical and economical. Before excavation is started, however, an upslope survey should be made

to determine whether excavation will alleviate or aggravate the situation. Fig. 17-9 perhaps makes the point aided by a caption quoted from Dr. Ladd, "Excavate! And watch the break move uphill. It can go half a mile; perhaps a mile." If excavation does seem advisable, it is probably wise in many instances to remove upslope portions first, rather than to start excavation at the toe of the slide. Hydraulicking has been used successfully and economically in removal of slide material. Removal of unusual loads or parts of the upper portions of the slope may prevent further movement.

In Dr. Ladd's words,[5] however, "Toe removal is an expedient, not a remedy. Generally it is a bad expedient, especially if there is great extent and background to the material that is moving."

*Slope Treatment.* Slope treatment includes a variety of practices, among which are slope reduction, consolidation, protection against undercutting, and surfacing.

Well-drained granular material of noncohesive type has an angle of repose, usually between 30-35°, that often can be reached by slope trimming. For fine-textured, clayey, cohesive soils no definite repose angle exists: the angle of stability changes with height of slope. Observation of undisturbed natural slopes of the same type of earth in the vicinity is probably the best guide to safe slope angles. Some clays literally have no safe angle of slope.

Consolidation consists of grouting cracks and joints in fractured rock and guniting surfaces. Grout not only adds cohesive bond but also excludes water. In coarse, permeable soil, consolidation by impregnation with sodium silicate or similar chemicals has been successful. Recently electrochemical stabilization of clay has been introduced; for some types of clay the method, still experimental, holds promise.

River, lake, or sea shores are locally undermined by erosion to the extent that slides take place. Various devices for erosion control are used including riprap, protective walls, and groynes. The use and effectiveness of these devices are discussed in the chapters on rivers and seas.

[5] Ladd, G. E., *op. cit.*, p. 1131.

Locally areas of relatively small size have been surface treated with oil or bituminous cover. The treatment excludes water and stabilizes the surface. Various types of vegetation also have been used for protective cover. A vegetation mat retards slope wash, gullying, and creep. As protection against mass movement involving much depth, however, vegetation is of little use. Insofar as vegetation increases infiltration and inhibits surface drainage, it may do more harm than good on potentially moving ground.

*Retaining Structures.* Many types of retaining structures have been built. All are designed to prevent earth movement by force. In many places they are economical and entirely successful. Retaining walls and cribbing should be used, however, only where the material they are designed to hold back is of small amount or is nearly stable when saturated. They are most effective against coarse granular material and broken rock, to prevent dribble. Properly buttressed, anchored, tied together, and drained, retaining structures have their uses and give a clean attractive look to highway cuts.

Retaining structures, however, have often failed. Many of the failures have taken place where the structure was used to hold back plastic material. The engineer should remember that retaining structures "should be designed for a predetermined load which they are to transmit to a foundation bed of known capacity." For many slopes it is not feasible to calculate the load which may be exerted on the structure. It is difficult and often impossible to determine the amount of material potentially in transit down slope. Additional material from above may be added to the moving mass. Hydrodynamic conditions may set up fluid pressures against a retaining structure which was not designed for that type of pressure. Too frequently, retaining structures simply transmit the load to a lower part of the material affected by the slide.

*Drainage.* Drainage is the most generally effective and practical control measure to curb earth flows and slides. Some engineers state categorically that water is always the cause and drainage always the cure; although the statement is comparable to the wartime slogan that the only good enemy is a dead one, there is much truth in it.

Any effective means of reducing the water content of a moving or unstable mass restores a measure of the stability that was lost when the water entered. It is the water that penetrates the slide that does the damage. The sources of entering water, therefore, are to be found and entry cut off if practical. Diversion and drainage works, upslope, to conduct the water to safe disposal channels are locally possible. Sealing any cracks or joints, oiling, or other waterproofing treatment aids in the exclusion of water. Because slight movements and even desiccation of unconsolidated material often result in cracks that should be filled, periodic slope inspection should be a routine part of maintenance.

A sliding or flowing mass can often be stabilized by installation of proper drainage within the material. If the slopes are gentle, say 25°, the lower part perhaps can be stabilized by drainage—surface and subsurface—to the extent that it stands as a natural large-scale retaining wall. Threatening masses, also, can be isolated or insulated by proper drains looping around the top and sides of the mass in the shape of an inverted letter U. Electro-osmotic stabilization of soils too fine to drain successfully by conventional methods has been reported successful from several projects. Electro-osmotic stabilization is based on the principle that water in capillaries flows from a plus to a minus electrode. The water moves through the soil under the influence of an EMF to a hollow cathode and is removed from the soil. The first use of this method reported was the stabilization of a long 6-foot-deep cut in silty clay at Salzgitter, Germany, in 1939.[6] The clay was yielding to flow, and the bottom of the cut was so soupy that excavation was held up. Along a 300-foot trial section, well points 30 feet apart were driven to a depth of 22.5 feet along the top of both sides of the cut. The anodes were driven halfway between the cathodes, and a potential of 180 volts applied. In a few hours it was possible to resume the work. The energy consumed is reported to have been about 1 kilowatt hour per cubic yard of excavation.

Fill slides have caused many a delay and much extra expense in

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[6] Casagrande, Leo, "Electro-osmotic Stabilization of Soils," *J. Boston Soc. Civil Engrs.*, Vol. 39, 1957, pp. 51-83.

construction. The working principles involved are the same as in naturally emplaced material. Adequate drainage of the fill material and prevention of water ingress are just as important in fills as for natural deposits. Some railway and highway fill failures have been caused by water conducted into the fill by the coarse ballast or road base material, sloping downgrade to the fill. Cut-off drains at the ends of the fill may save far more than their cost. Other sources of water entry often can be discovered and cut off. Provision for drainage and water exclusion can be more economically and effectively installed during construction than at a later date. If fills of capillary soil mixtures are to be placed on wet ground, as they so often are, the fill should rest on a gravel base course 8 inches or more thick.

Before any program of remedy for flow or slide is undertaken, a survey of the geological conditions that are responsible must be made. "Method-selection, where control seems possible, must depend upon understanding of what is sliding, how much material is involved, what its distribution is, and what the causes are. What? How much? Where? Why?" [7]

Prevention is better than remedy. Perhaps a better knowledge among engineers of earth movements, a knowledge that results in more critical route surveys and more vigilant slope inspections and better measures for control of water, is the best basis for prevention.

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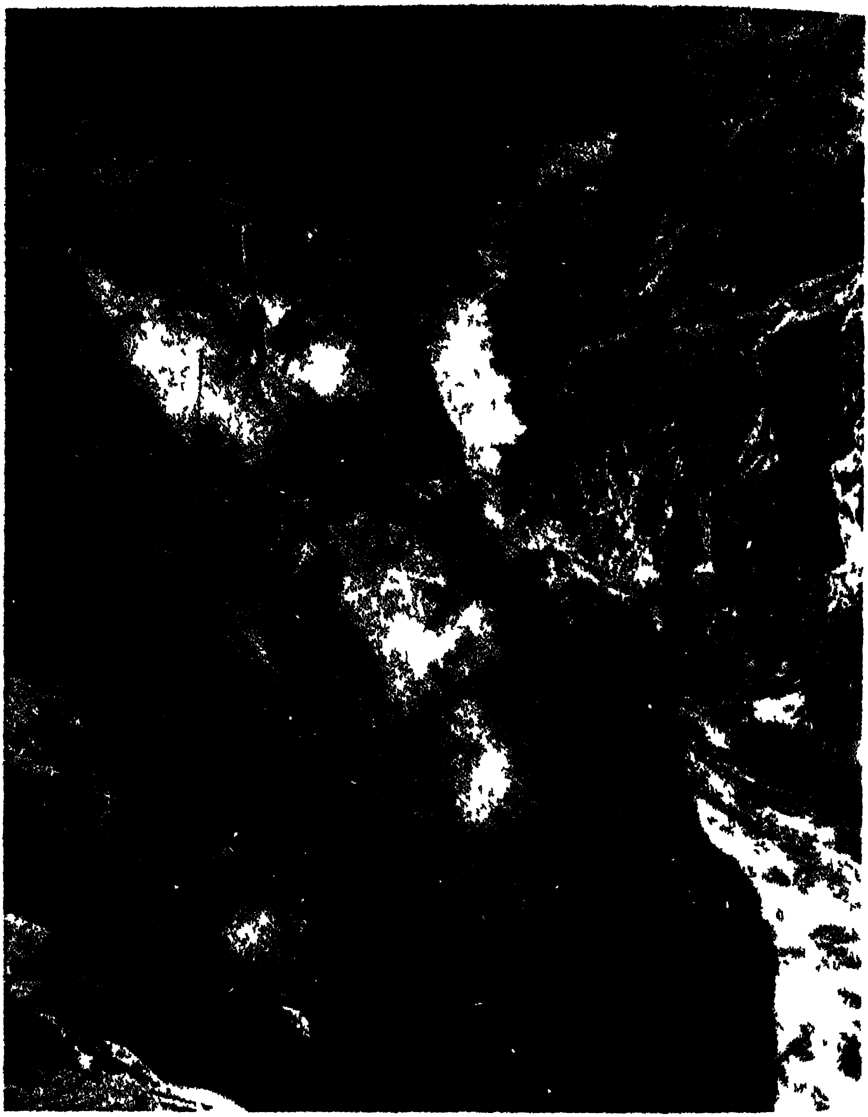


**A Dam Site on the Cowlitz River, Mayfield, Washington**

# CHAPTER XVIII

# STREAMS

IN THE HISTORY OF THE EARTH'S LAND AREAS, SOMETIMES one agent and sometimes another has been dominant in shaping the surface. At present the continents are high and for the most part well clothed with vegetation, glaciers are largely restricted to the high latitudes, and the work of running water is dominant. Streams are estimated to carry about 8000 cubic miles of water to the seas each year. Thus, the flow of rivers amounts to approximately $22 \times 10^6$ mgd or to some 254 million gallons per second. The development and utilization of stream power to economic ends have gone ahead in most countries; and in some, particularly those lacking the mineral fuels, water-power utilization has approached the economic limit. Much stream energy is devoted to erosion and transportation of sediments. It is inevitable that streams present many practical everyday problems. Bridges must be built, and the utilization of stream power, the creation of reservoirs for irrigation, flood control, and water supply and the regulation of rivers for navigation and flood abatement present engineering problems which are met in every state. Some deposits of both past and present streams are economic sources of construction material. Conversely, some stream deposits clog channels, fill reservoirs, or damage developed land. The fundamental concepts of stream characteristics and stream action are a necessary part of the engineer's training.

## Stream Work

The prime function of streams is to drain surplus waters from the lands. In carrying out this function, streams erode valleys for

themselves, pick up and transport rock debris, take some material into solution, and build deposits of sedimentary materials. Erosion, transportation, and deposition, therefore, are the major divisions of stream work.

***Stream Erosion.*** By *stream erosion* is meant the mechanical or chemical removal of material encountered by the stream. To a limited extent, streams dissolve rocks, especially those of the carbonate group. This chemical work locally is evidenced by solution pits along the stream course. Streams erode, that is remove material from their beds and banks in several different mechanical ways Although more experimental work must be done and more field observations gathered before the processes are fully understood and reduced to quantitative expression, three ways are suggested by which streams may pick up particles. These are by impact, by frictional drag, and by hydraulic uplift.

If a particle is to be removed by impact, the component of current force in the direction of dislodgment must be greater than the oppositely directed component of weight of the particle. Thus if equidimensional particles are considered, of a shape such that volume is proportional to diameter (spheres for example) and further, if roughness of surface of stream bed and particle and specific gravity of the particles are considered at least statistically uniform, it can be shown that the weight or volume of the particles moved varies with the sixth power of velocity; or stated in terms of (particle) size, the radius varies with the square of the velocity. Thus, if current velocity is doubled, the radius of a spherical particle that can be moved if fully exposed to the current is four times that of the similar sphere just moved at the lower velocity. According to Ruby,[1] the so-called sixth power law ($R^3 \propto v^6$, where $R$ is the radius and $v$ is the current velocity) is more nearly applicable to coarse sand and gravel than to fine sediment.

If a particle is to be moved by frictional drag, the friction between the running water and a particle on the bottom of the stream

[1] Ruby, W. W., "The Force Required to Move Particles on a Stream Bed," U S Geological Survey, Professional Paper 189 E, 1937, p. 129.

must exceed the weight component of the particle opposed to movement. The fundamental equation for this concept, expressing tractive force per unit area, is the Du Boys formula,[2]

$$T = \rho S d$$

where $T$ is the tractive force, $\rho$ is the density of the water, $S$ is the sine of the slope angle of the water surface, and $d$ is the depth. Because this expression eliminates velocity, which at the bed of a stream is very difficult to measure, it is favored by most engineers concerned with bed-load movements. For practically all streams, the tangent of the slope angle can be considered essentially equal to its sine, and the depth-slope product requires only easily made measurements. This formula or derivatives from it are applicable only to loose material. Ruby[3] has shown that for experimental data analyzed in his study, the critical tractive force concept is more nearly true for fine sand than for coarse sand or gravel.

If a particle is to be lifted by hydrodynamic uplift, the lifting force must be greater than the submerged weight of the particle. The velocity of stream flow increases upwards from the bottom of a stream to a maximum at some distance below the surface, as shown in Fig. 18-1. The velocity increase is especially rapid close to the bottom. At the points where fragments rest on the bottom, velocity is zero and correspondingly, the velocities just above must be greater than the average. Thus higher pressures at the base and lower pressures above the particle result, and the upthrust may be enough to lift it.[4]

The preceding discussion has indicated methods by which streams may erode their channels in loose materials. Clear water, however, has relatively little effect on consolidated rock at velocities ordinary in streams. But the abrasive effects of particles carried by the water are marked indeed, and the bulk of stream erosion in consolidated

[2] A simple derivation of this formula is given by Matthes in the *Transactions of the Am. Soc. Civil Engineers*, Vol. 100, 1935, p. 845.

[3] Ruby, W. W., *op. cit.*, p. 128.

[4] For a discussion of this principle see: Hjulstrom, F., "Studies of the Morphological Activities of Rivers as Illustrated by the River Fyris," *Bull. Geol. Inst. of Upsala*, Vol. 25, 1935, pp. 267-270.

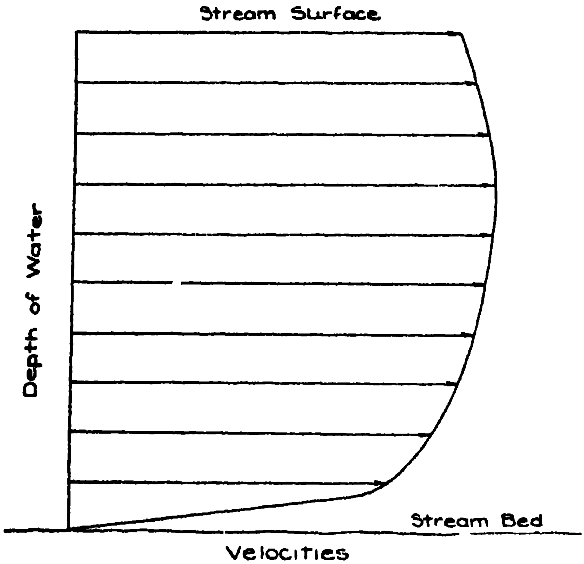



FIG. 18 1. Typical vertical velocity curve of a stream. Steep velocity gradient near stream bed and parabolic distribution of velocities above. (From W. W. Ruby, Professional Paper 189 E, U. S. Geological Survey.)

rock must be ascribed to abrasion. The abrasive effect of a particle on other particles or on bedrock is in proportion to the product of its mass and velocity. The rate of particle movement varies from zero to the velocity of the water current; hence, the abrasive ability of a stream cannot be expressed as a simple exponential value of velocity. The abrasive resistance of particles and of consolidated rocks, likewise, is variable and further precludes numerical evaluation of abrasive ability.

Abrasive effects which result from impact and scouring by materials carried in streams are locally noteworthy. Perhaps the best known and commonly seen of these are the pot holes found at the base of so many waterfalls. In most pot holes there can be found pebbles worn smooth by the ball milling which has cut the hole. At some places, gorges have been formed by the coalescence of pot holes cut in sequence as a waterfall has retreated upstream.

From what has been said concerning mechanical erosion, it is obvious that the velocity of a stream is a very important factor in its effectiveness as an erosive agent. The velocity of the stream de-

pends upon slope, volume, and channel configuration. An empirical statement is the *Chézy* formula,

$$V = C\sqrt{RS}$$

where $V$ is the mean velocity, $C$ a coefficient which varies with the the characteristics of the channel (individual for a considered section

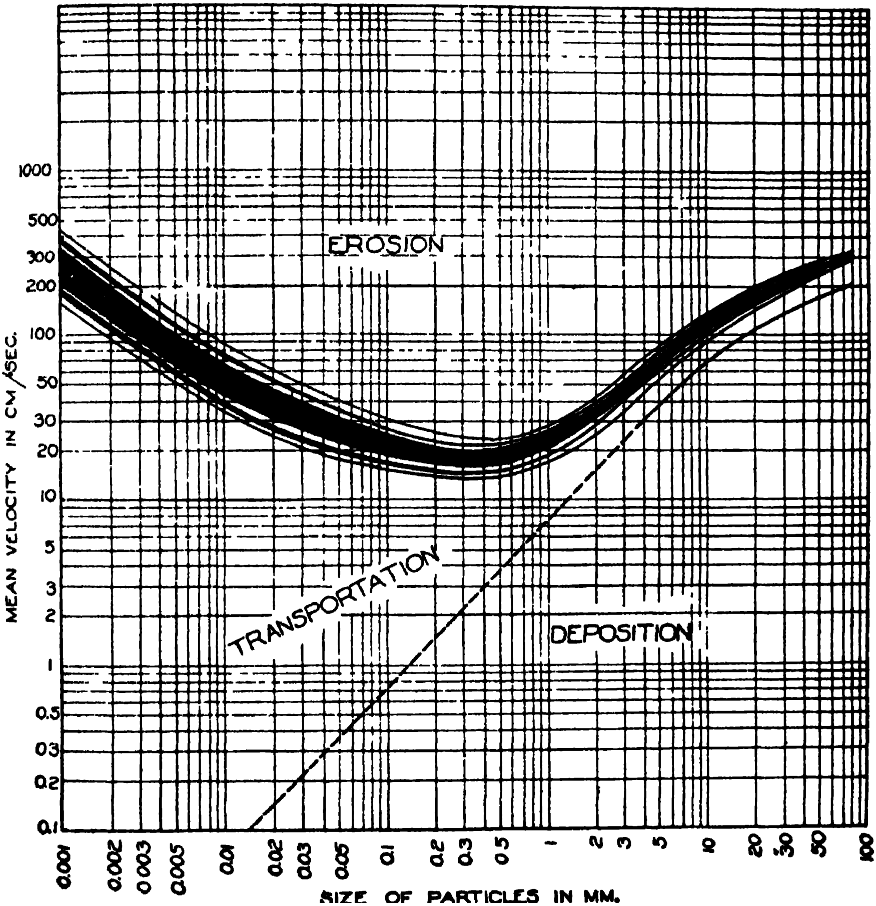



FIG. 18-2. Fields of erosion, transportation, and deposition for well-sorted sediments. (After Hjulstrom)

of any stream), $R$ the hydraulic radius, which is the cross-sectional area divided by the wetted perimeter, and $S$ the slope. Many efforts

have been made to obtain a simple and generally applicable expression for the Chézy $C$. The Manning formula,

$$V = \frac{1}{n} R^{2/3} S^{1/2}$$

where $n$ is the coefficient of roughness, is in common use. In foot-pound-second units this becomes

$$V = \frac{1.486}{n} R^{2/3} S^{1/2}$$

which can be considered the Chézy formula with $C = \dfrac{1.486}{n} R^{1/6}$. Values for $n$ for use in the Manning formula, which are of suggestive value are:

| | |
|---|---|
| a. Channel clean, straight, no pools | 0.025-.033 |
| b. Channel with weeds and stones | 0.030-.040 |
| c. Channel with large stones | 0.045-.060 |

The velocity required to initiate movement, i.e., erosional velocity or critical bed-velocity, is significantly higher than that required to maintain movement. The relations shown in Fig. 18-2 illustrate for uniform materials the ranges of current velocities for erosion, transportation, and deposition. Sufficient data for the establishment of similar curves for natural mixtures of grade sizes are not yet available. However, laboratory data from a number of determinations are summarized in Table 18.1.

It has been estimated that the erosional velocity is some 29 per cent higher than the velocity necessary to maintain bed-load movement. The finer grades of material, i.e., clays and silty clays, are more erosion resistant than loose sands; further data are needed, however, on the erodability of fine-textured soils, particularly under natural conditions. Table 18.2 presents additional data for non-cohesive soils.

***Stream Transportation.*** The amount of sediment transported to the seas each year reaches staggering proportions. A few figures will make the point. The Mississippi probably carries more than

TABLE 18.1. CRITICAL BED VELOCITIES FOR DIFFERENT GRADES OF DEBRIS

| Radius (cm) | | Critical Bed Velocity at which Movement Starts (cm/sec) * |
|---|---|---|
| Minimum | Maximum | |
| 0.0155 | 0.0200 | 13.7 – |
| 0.0290 | 0.0450 | 15.2 – |
| 0.0450 | 0.105 | 17.9 + <br> 18.0 – |
| [0.135] | 0.175 | 29.7 – |
| 0.175 | 0.250 | 36.2 + <br> 36.4 – |
| 0.250 | [0.370] | 44.7 + <br> 45.9 + |
| 0.0295 – | 0.668 | 35.9 |

* Calculated by Ruby from data of Gilbert.

TABLE 18.2.* LIMITING TRACTIVE FORCE (LB./FT.²) FOR NON-COHESIVE MATERIALS

| Median Size, in mm. | Clear $H_2O$ | Light load of fine sediment | Heavy load of fine sediment |
|---|---|---|---|
| 0.1 | 0.025 | 0.050 | 0.075 |
| 0.2 | 0.026 | 0.052 | 0.078 |
| 0.5 | 0.030 | 0.055 | 0.083 |
| 1.0 | 0.040 | 0.060 | 0.090 |
| 2.0 | 0.060 | 0.080 | 0.110 |
| 5.0 | 0.140 | 0.165 | 0.185 |

* From E. W. Lane, *Trans. Am. Soc. Civil Engrs.*, 1955.

730,000,000 tons of sediment per year to the lower delta.[5] Measurements over a seven months' period (January to August, 1927), by the Mississippi River Commission showed an average daily suspended load of 103,960,000 cubic yards per day, equivalent to a minimum of 1,500,000 tons. Although, of course, extension is irregular both in time and place, it appears that the delta is extending at an average rate of more than 85 feet per year. On every continent but one, streams are at work, and the net result is a shift of land material to the seas in amount, which, if uniformly derived, perhaps is equivalent to an over-all lowering of the land surfaces at a rate of about one foot in five thousand years. Were it not for the internal forces of volcanism and uplift, the continents would have been reduced long ago to or below sea level.

The mechanics of erosion have been indicated. Other sources of stream load, however, are more important than bed and bank erosion by the stream itself. Every rain washes material from slopes into the stream. Slope wash constitutes the largest fraction of load of most streams. Where banks are oversteepened or undercut by stream erosion, flows and slides contribute to the stream load, and ground water not only adds volume to the stream but also contributes mineral matter.

From the foregoing, it is apparent that stream loads travel in three ways: by movement along the bed, by suspension, and by solution. To date no attempts have successfully correlated total loads with velocity, discharge, slope, or depth.

*Bed Load.* The *bed load* is that part of the stream-carried debris that slides or rolls along the bottom. The *competency* of a current is a statement of its ability to move materials in terms of particle size. Thus a stream may be *competent* to move a sphere of one inch diameter. Geologists commonly state that competency varies with the square of velocity. Experimental data, however, suggest that frictional drag as well as impact contributes to competency, and that competency and velocity must have a somewhat different expo-

[5] Russell, R. J., "Lower Mississippi River Delta," *La. Geol. Survey, Bull. 8,* 1936, p. 162.

nential relation. Engineers commonly state that competency varies with the slope-depth product and, by a derivative of the Du Boys formula, calculate the mean size of particle that can be moved. By this relation a deep, slow stream of gentle slope is held to be as competent as a shallow, swiftly flowing stream of steeper gradient. The difference in views is more apparent than real, however, for engineers have worked largely on the practical problems of river sedimentation presented by alluvial streams of relatively low velocities carrying fine grades of sediment in the size ranges where the Du Boys formula is reasonably successful. Matthes,[6] for example, states that those reaches of the Lower Mississippi free from shoaling have slope-depth-particle size relations conforming to this view of competency.

*Suspended Load.* Stream flow is turbulent. There are upward currents as well as currents in diverse directions that keep sediment in suspension. The suspended load of many streams is considerable. However, although many streams are so charged with suspended material, both organic and inorganic, as to appear very muddy, the percentage by weight of mineral material is generally small. For example, the Missouri River ("Big Muddy") seldom carries over 20,000 parts per million.[7] Nevertheless, some large rivers have been reported to carry at times as much as 68 per cent bv weight of silt in suspension, and mudflow can be considered as a type of sediment-charged stream.

Locally, along a stream, material may travel by *saltation,* a form of travel partly by traction along the bed, and partly by suspension. By this method of progression a sedimentary particle describes a series of leaps and rolls.

It has been found that the suspended material of most streams constitutes the bulk of material carried. In the Mississippi, for example, the ratio to bed load is on the order of eight or ten to one. Measurements of the quantity of suspended load are more easily

[6] Matthes, G. H., *op. cit.*, p. 846.
[7] Straub, L. G., *Hydrology*, 1942, p. 624.

and more accurately made than are the corresponding estimate of bed load.

*Dissolved Load.* Besides the material carried mechanically, much is carried in solution. Part of the dissolved mineral matter is obtained from the rocks over which the stream or its tributaries flow. The larger portion, however, is brought in by the ground waters tributary to the stream.

***Quality of Stream Waters.*** The quality of stream waters depends upon the dissolved and suspended material carried. Quality is of economic interest because different uses require certain standards of purity or place limits upon various types of impurities, both physical and chemical. No handbook of ready reference, setting forth the qualities of stream waters, can substitute for specific quantitative data gathered at the time and place where needed for the specific purpose involved. Qualities of stream water, however, do show regional differences which are related to the geological and geographical differences of their drainage basins. These differences of quality are of interest and significance according to the proposed use of the water whether for domestic and drinking supply, industrial use, for boilers, for irrigation, or for other utilitarian purposes The following summary presents representative data for regions of different types and indicates qualitatively the chemical and mechanical loads transported by streams within the selected regions.

*Chemical Composition of Stream Waters.* As has already been shown, the chemical composition of stream waters varies; streams derive dissolved substances from the ground waters which nourish them, from the rocks over which and through which they flow, from the mechanical sediment load which they carry, and from pollution by sewage, industrial wastes, and other minor sources. Table 18.3 presents water analyses of representative streams.

Analyses 1, 2, and 3 are representative of Atlantic Slope streams. The headwaters of these streams are generally quite pure; many of the streams rise in crystalline rock areas. In common with many eastern rivers, the composition is modified by waste water from pulp,

TABLE 18.3.* WATER ANALYSIS OF REPRESENTATIVE STREAMS

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $CO_3$ | 20.29 | 24.93 | 21.32 | 51.65 | 33.23 | 34.98 | 11.55 | 30.14 | 42.01 | 41.93 |
| $SO_4$ | 24.85 | 4.90 | 8.49 | 1.05 | 21.74 | 15.37 | 30.10 | 12.21 | 13.08 | 10.37 |
| Cl | 4.76 | 6.34 | 3.96 | 0.48 | 3.79 | 6.21 | 21.65 | 5.79 | 0.84 | trace |
| $NO_3$ | —— | 0.43 | 1.32 | —— | 1.05 | 1.60 | —— | 0.48 | 0.16 | —— |
| Ca | 15.33 | 8.50 | 9.06 | 22.94 | 17.08 | 20.50 | 13.73 | 11.45 | 21.40 | 23.25 |
| Mg | 2.27 | 2.59 | 1.51 | 4.09 | 6.22 | 5.38 | 3.03 | 5.59 | 6.35 | 4.39 |
| Na | 5.17 | 10.09 | 12.08 | 5.14 | 8.15 | 8.33 | 14.78 | 9.78 | 7.14 | 5.61 |
| K | 2.07 | 1.87 | 3.40 | 1.75 | | | 0.85 | 1.68 | | |
| $SiO_2$ | 18.63 | 37.47 | 37.73 | 9.40 | 8.54 | 7.05 | 3.83 | 19.12 | 9.16 | 14.39 |
| $Al_2O_3$ | | | —— | 2.01 | —— | 0.45 | 0.48 | 3.35 | 0.06 | 0.06 |
| | 6.63 | | | | | | | | | |
| $Fe_2O_3$ | | 2.88 | 1.13 | 1.49 | 0.20 | 0.13 | | 0.41 | | —— |
| Salinity (parts per million) | 48. 3 | 73 | 52 | 195 | 269 | 166 | 791 | 118. 5 | | |

1—Androscoggin River, Brunswick, Me.
2—Neuse River at Raleigh, N. C.
3—Chattahoochee River, West Point, Ga.
4—Mississippi River, Brainard, Minn.
5—Mississippi River, Chester, Ill.
6—Mississippi River, New Orleans, La.
7—Rio Grande, Laredo, Tex.
8—Sacramento River, Sacramento, Calif.
9—Columbia River, Pasco, Wash.
10—Yukon River, Between White Horse and Selivgn.

* From *Data of Geochemistry*, F. W. Clark.

paper, and other mills. Note the high sulfate content which is largely the result of pollution.

The next three analyses 4, 5, and 6, show the contrast between the upper and lower Mississippi River waters. Sulfates and chlorides increase downstream. In part, the chlorides are due to pollution but, together with the sulfates, are derived in large measure from the western tributaries. Carbonates, calcium and magnesium, are higher than those shown by the eastern seaboard streams, reflecting the greater abundance of limestone and dolomite through which the waters pass.

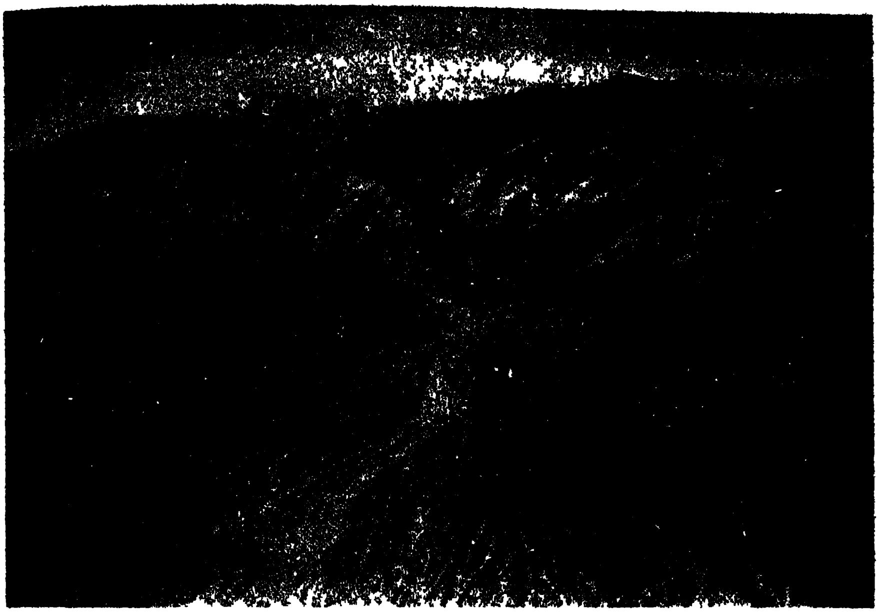
Analysis 7 is one taken from the Rio Grande. The high salinity and predominance of alkali sulfates and chlorides are the outstanding characteristics of stream waters of this dry region.

The last three analyses, 8, 9, and 10, are from Pacific Coast streams. The more northern rivers show an increase of calcium and magnesium with decreasing sulfate and chloride content.

Chemical analyses of stream waters reflect the influence of both the geology and climates of the regions through which they flow. Streams of crystalline rock areas tend to have a low salinity and a relatively high silica and alkali content. In the humid regions, for example eastern or northwestern North America, where vegetation is abundant, carbonate waters prevail, and calcium correspondingly is high. In the drier regions, for example the Southwest, sulfates and chlorides are relatively high. The larger the stream and the greater its drainage basin, the nearer the waters approach the mean.

***Stream Deposits.*** Changes in the depth-slope product or in the velocity or turbulence of streams result in a variety of stream deposits. Some of these are useful; some are detrimental. The principal stream deposits are alluvial fans, natural levees and flood plains, channel deposits, deposits related to curves, and deltas.

***Alluvial Fans.***[4] An alluvial fan is a stream deposit built where the gradient of a stream is abruptly decreased. The deposit has roughly the shape of a surface section of a broad cone, apexing towards the point where the stream gradient breaks, as shown in Fig. 18-3. They are often called *alluvial cones.* Alluvial fans are



Spence Air Photos

FIG 18-3 Alluvial fan, Death Valley, California.

especially characteristic of regions where mountain slopes rise steeply from adjacent plains. They are numerous, therefore, along many of the western ranges. The coalescence of alluvial fans along the range or mountain front forms composite cones or *alluvial aprons.* In the drier regions many perennial mountain streams disappear from the surface near the apex of the cone to flow through the fan material. During times of flood, however, the stream, charged with sediment, may flow violently down the surface of the fan, gouging out steep-walled valleys called *arroyos,* and bring much sediment to the lower part of the fan. The deposits generally have steeper slopes and coarser, more unevenly graded material in the upper portions than they do in the lower portions, although for small fans the differences may not be great.

*Natural Levees and Flood Plains.* Streams that flow in valleys with relatively broad, flat floors often spill out over the banks and inundate the bordering lands. Bank zones are flooded first and flooded more frequently than more distant parts. Hence alluvial

deposits as broad low ridges are built along the banks. These are called *natural levees*. The lowland areas along the stream, which are flooded, also receive sediment. River plains of alluvial deposits are built up, merging with the natural levees. These plains of river deposit are called *flood plains*. A profile showing natural levees and adjacent flood plains is shown in Fig. 18-4. The natural levees and flood plains of large streams are commonly composed of fine sand silt, and clay-sized particles. The remarkable endurance of the soils

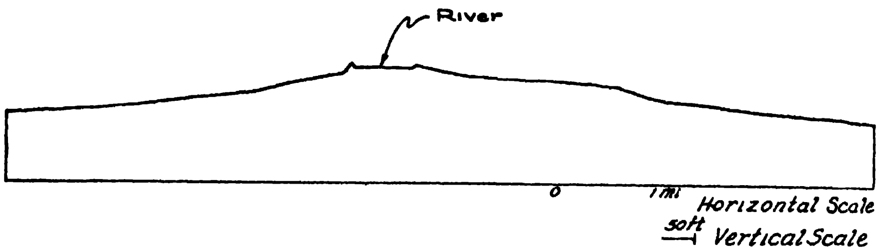



FIG 18 4 Transverse profile of natural levees

of the great flood plains of the Nile or the Hwang Ho that have been under continuous cultivation for many generations is a result of annual increments of alluvium. Because of the fertile soils, many flood plains are densely populated; perhaps between a quarter and a third of the world's population lives on flood plains Flood protection therefore becomes an engineering problem of high significance for these areas.

*Channel Deposits*. Channel deposits, called *bars* or *shoals*, are built wherever the competency of the stream drops below that required by the grade size of particles carried. The velocities and depths of streams and the location of threads of maximum currents fluctuate for any stream. The cross-sectional areas are not constant nor are the volumes or discharges. The loci of erosion and deposition, therefore, are subject to shifts and are of irregular disposition

Bars or shoals are found in the straight reaches between the bends of many streams. In these straight reaches, the width of the channel often increases; and, in these stretches, the swift water currents, deflected from the outside of the upstream curve, cross to

impinge on the outside banks of the next downstream bend. The spread and retardation of currents thus localize the construction of many river shoals. Other changes in cross-sectional area or in channel configuration cause local channel deposits During floods, the tops of shoals are often built up and the deeps scoured. During lower or slack water periods, the shoals are scoured and the deeps

FIG. 18-5 Extension of natural levees at the mouth of the Shabogama River, Quebec. (Canadian Geological Survey)

receive sediment. Most channel deposits are therefore the result of alternate cut and fill.

Channel deposits consists of various grades of sediment according to the competency of the stream currents which build them. All tend to be lenticular in shape, and all show cross-bedding.

*Deposits at Curves.* Where a stream makes a pronounced bend or meander, the swiftest currents and deepest water swing toward the outside bank. The result is concentrated erosion on the outside of the curve and the construction of a *slip-off* slope, i.e., shoaling on the inside of the curve. The helical flow of streams, illustrated in Fig. 18-6, together with turbulent diffusion, carries sediment from the deep, swift-flowing portion of the stream on the outside of the

FIG. 18 6 Helical flow in stream (From L. Staub, in "Hydrology," National Research Council)

bend to the shallow, slow-flowing, less turbulent waters of the inside of the bend where it is deposited. Thus as erosion cuts away banks on one side, the opposite side is built out, and the stream migrates laterally.

*Scour and Fill.* On the Fraser River, at Mission, British Columbia, a 150-foot section of a steel bridge fell into the river because of a pier failure by scour. A 90-foot hole was scoured adjacent to one of the piers during a flood. Subsequently the scour holes were filled with rock and a 10-inch-thick concrete floor laid for the full width of the stream 100 feet upstream and 60 feet downstream.[8]

Engineers have long had to contest scour and fill changes in channels of alluvial streams. From the preceding discussion of channel characteristics some inferences as to scour and fill can be drawn For many engineering works these phenomena are of significance and for some are critical. On the basis of gauging-station data, it can be shown that frequently the depth of the stream in flood is greater than normal flow depths plus the rise of water surface due to the flood water addition. This indicates channel deepening during the flood stage. Similarly with receding floods, there is a greater decrease in depth than loss of the flood heights alone. Gauging stations however, are commonly situated in narrow segments of the stream for convenience in placing cable ways, or on bridges where piers induce scour. Where dams have been built—likewise generally in narrow reaches of streams—evidence of scour and fill have been obtained. For example, at Hoover Dam, sawn timbers discovered 50 feet below the low-water surface and 40 feet below channel bottom indicate recent scour and fill at that place. Many other examples could be given of deep scour and fill; data from other studies, how-

[8] Eng. News Record, 1956, pp. 70-72.

ever—particularly in connection with the filling of reservoirs—indicate that such scour and fill is not continuous along the length of the stream. During flood conditions the deep scour indicated by data from narrow sections where gauging data are taken is complemented by deposition in the straight and somewhat wider and shoaler sections. The scoured deep sections tend to be filled during low-water stages following the flood stages, and the areas of flood deposition are eroded.

Where river sections are constricted, as by bridge piers or meander cut-offs to straighten the course of the stream, scour may be induced and take its toll, especially during flood flows. Terzaghi[9] estimates that for every foot of flood rise above normal flow levels in alluvial channels scour may amount to three or four feet.

*Deltas.* Deltas are deposits built at the mouths of streams. Although marine deltas are best known, deltas are also built in lakes and even may be built where one stream flows into another. Deltas

FIG. 18-7 Elevated delta, used as source for sand and gravel. Note ripple mark in topset beds

are generally flat-topped and characteristically have pronounced frontal slopes and lobate outlines. The material of most deltas is well sorted, and many deltas are uniformly graded. If there is a difference in grading, the coarsest material is generally found on the

[9] Terzaghi, K., "Failure of Bridge Piers Due to Scour," *Proc 1st International Conf. on Soils Mechanics and Foundation Engineering,* Vol II, Cambridge, 1936.

landward side, grading into finer material in the direction of deeper water.

Delta building is favored by an abundance of sediment in the stream, lack of strong waves or currents in the waters receiving the stream, a stable water level of lake or sea, and salinity of the sea. Salt water acts as a coagulator of the clay fraction of the sediment and promotes sedimentation. On the Atlantic seaboard, most of the streams run comparatively clear, and the shoreline has been unstable, hence the lack of notable deltas.

Many deltas are found above the present strand lines of both lake and sea. The tops of these are used in establishing the elevations of former water planes. At many places, these "stranded" deltas are important sources of sand and gravel suitable for construction (Fig 18-7).

### The Normal Development of Streams

Just as the individuals of any organic species (man included) normally develop according to the specific pattern, so streams have a normal course of development. Indeed, some of the terminology describing the stages of human development has been redefined and applied to stages of drainage development: for example, youth, maturity, and old age. Anyone concerned with stream work can more easily and analytically approach the problems involved if possessed with an understanding of stream development, stream types, and the associated features. To this end, the origin of streams, two fundamental concepts of stream activity, and the three principal stages of stream development are briefly discussed.

***Origin of Streams.*** No land surface is ever without irregularities. The surface runoff flows down the slopes and collects in hollows and sags. As a hollow is filled, it overflows its rim at the lowest place, and the overflow moves downgrade to the next basin. In this way an imperfect drainage system is established. Once a concentrated flow of the runoff is established, a valley or gully develops (Fig. 18-8). New valleys are developing all the time, and as has been pointed out repeatedly, gullying is a real menace to thousands of acres of

agricultural land. Gullies extend by headward lengthening and by the formation of tributary gullies. Headward extension of gullies is explained rather simply by the fact that more water commonly runs into a depression at the upslope end than from the side slopes. Inequalities of erodability of the soil and irregularities of initial slope give rise to the crooks and bends of headward extension and to the irregular development of tributary gullies. Most valleys occupied by permanent streams have been cut deep enough to reach the saturated zone (water table). Once a gully has deepened so that

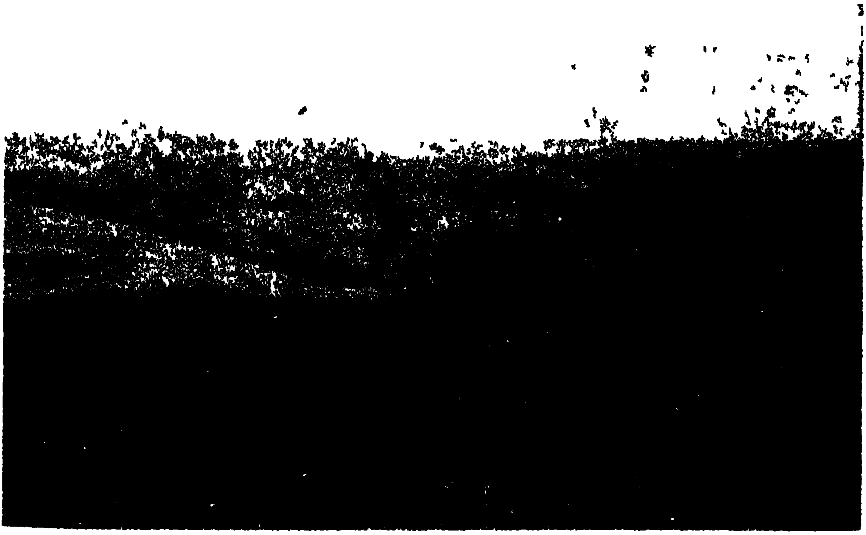


Fig 18 8 Development of gullies. (U S Soil Conservation Service)

its bottom is below the saturated zone, it no longer loses water to the ground by infiltration but rather draws water from the saturated soil or rock.

***Two Fundamental Concepts.*** Before proceeding further with the discussion, it is necessary to present two basic physiographic concepts, that of base level, and that of profile of equilibrium.

*Base Level.* The level which controls the depth of stream erosion is called a *base level.* It is obvious that no stream can cut much below the surface of the body of water to which it is tributary In

other words, it is normal for a tributary stream to join its master stream at an accordant level. The ultimate base level of all streams is a level slightly below that of the seas; for except for streams flowing into the few deep interior basins, no stream can cut much below sea level. Lakes and streams serve as *temporary base levels* for their tributaries. Other temporary base levels which affect the course of stream development are obstructions to down-cutting encountered by a stream. The obstructions may be resistant rock strata, dikes, sills or other intrusives, or lava flows or dams constructed by man. The valley upstream from a temporary base level can be lowered no faster than the temporary base level is cut down; if the valley floor is cut down to that level, the upstream section of the stream eventually becomes graded with respect to the temporary base level, the valley above the obstruction widens out and takes on a somewhat different aspect because of it.

*Profile of Equilibrium (Grade).* That streams must have a slope to flow over is obvious; they cannot reduce their valleys to sea level except in the lower reaches. A stream is said to be *graded* or to have reached its *profile of equilibrium* when its slope and volume are in equilibrium with the sediment load transported. This condition of balance or equilibrium is with reference to the average-sized material on its bed. It should be recognized that no stream at any time or place is ever at grade. Annual and seasonal fluctuations in volume and velocity bring about continual readjustments, and downward cutting never entirely ceases. Grade, or the profile of equilibrium, then, is an approximate condition of equilbrium only, and the scales are weighted in favor of erosion. Downward cutting does not cease entirely as the stream achieves grade, but after the graded condition has been reached, the proportion of down-cutting to lateral corrasion is greatly lessened. Often confused with grade is the term *gradient*. Gradient expresses slope, commonly stated in feet per mile.

***The Normal Stream Cycle.*** Geologists have found it convenient to describe the stages of stream development in terms of the so-called stream or valley cycle. The stream "cycle" is merely a recogni-

tion or grouping of stream features commonly associated in the course of normal drainage line development. No implication of years is to be read into the terms of this cycle. A "youthful" stream in hard rock, high above base level or far above the profile of equilibrium, for example, may be millions of years old, whereas an "old" stream, working in soft material near base level, may be only a few thousand years old.

*Youth.* Streams above grade, and consequently actively engaged in down-cutting, are called *youthful.* The more rapid the down-cutting and the more resistant the rock of the valley walls, the narrower is the youthful valley and the more steeply sloping are its side walls. In soft rocks, weathering and slope wash reduce the side wall slopes, and the valley is more "open." Under either condition, however, the youthful stream valley typically has a V-shaped cross-section; the V may be quite open, or it may be quite close as in gorges or canyons.

In the early stages of development, the drainage system consists of water-filled depressions, lakes, ponds, and swamps, connected by streams. As, in the course of time, the depressions are filled by sediment or vegetation and the outlets lowered by stream erosion, the lake-stream sequence gives way to a more perfected and integrated drainage system, and the number and length of tributary streams increase. In the youthful stage, also, waterfalls or rapids develop wherever sufficient differences in rock resistance are encountered in its bed by the down-cutting stream; the weaker rock downstream can be incised more rapidly than the resistant rock. The upstream deepening is retarded by the temporary base level of the resistant rock. Although the great majority of waterfalls owe their existence to differences in resistance of adjacent rocks, there are other causes for falls and rapids—for example, joints, erosion scarps, or other types of slope irregularities. Waterfalls and rapids are found in streams above grade; they disappear as the stream cuts down to the profile of equilibrium and becomes graded in the engineering sense. In summary the characteristics of youth are: lakes and swamps in the drainage line, waterfalls and rapids, and valleys of V cross section.

*Maturity.* When the youthful stream has cut down to an approximately graded profile, it is said to have become *mature.* No longer as actively down-cutting as the youthful stream, the effects of lateral cutting become relatively more prominent. The outsides of the bends are attacked, just as in youth, but more effectively because the channel is not being rapidly deepened. The results of the lateral corrasion are shown in the smoothing out of the crooks and bends of youth and by the development of more or less symmetrical loops called *meanders.* It is a matter of observation that many meanders have a radius of approximately seventeen or eighteen times the width of the stream The asymmetrical, downstream bulge of meanders can be seen on many maps and aerial photos The threads of maximum current stay on the inner side of a curve for perhaps a quarter of the loop before crossing to the outside. The downstream part of the outside of the meander is therefore most effectively worn away, and the meanders migrate downstream in a process called *sweep.* By this process, the spurs are trimmed away and the valley walls straightened and widened, as shown diagrammatically in Fig. 18-9.

One of the results of meandering—the cut-off—deserves special consideration. By the normal course of meander growth, the neck of a meander may become progressively narrowed and finally cut through. In the early stages of the cut-off, a part of the water continues to travel around the bend through the old channel; another part travels across the neck through the new channel. By decreasing the length of the stream, cut-offs increase the gradient. In time of flood, more water passes downstream in unit time than previous to the cut-off, because of the increased gradient and velocity, and flood crests reach downstream more rapidly because of the shorter distance the water has to travel. Just below the cut-off, the old gradient checks the velocity of the water coming through the cut-off, and the decrease in velocity is felt upstream for some distance in the cut-off. This velocity check may cause deposition in the lower end of the cut-off in the stream's effort to regrade itself. Above the cut-off for some distance there is an increase in velocity, and the change of

slope is rapidly distributed upstream from the cut-off in alluvial material. That part of the water that enters the old meander loop has its velocity checked because of the lower gradient and may de-

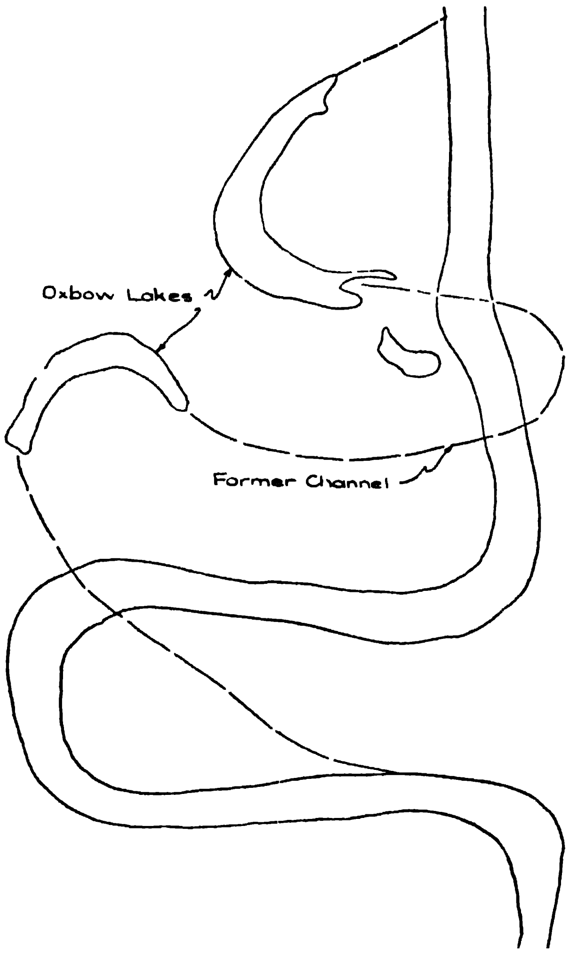



FIG. 18-9. Sweep in stream development: meanders not only shift laterally, but also migrate downstream.

posit sediment at that end of the meander, damming it off. The resultant lakes are called *ox-bows*. It appears from these considerations that flood danger above a cut-off is diminished because of the

increased efficiency of the stream. Those portions of the flood plains below the cut-off may be more liable to flood damage, however, for not only is more water passed downstream more quickly than before, but also the storage capacity of the old channel and its adjacent flood plains are no longer utilized.

One effect of cut-offs that may reach far downstream is a result of the change in direction of the current as it comes out of the cut-off as compared with its direction when the bulk of the stream flowed around the bend. Deflections of the currents may give rise to a whole new series of downstream impingement points. Some areas previously safe are subjected to erosion, and some areas previously being eroded are no longer scoured; thus new meanders are initiated, and old ones change position. In the process, the valley is further widened, and coincident with the broadening of the valley flats and the growth of flood plains, the slopes of the valley walls are gradually reduced by weathering and slope wash. Thus the cross section becomes one of broadly open V shape with a flat bottom.

It is well known that many mature (and old) streams are alluviating, i.e., building up their beds as well as their natural levees and flood plains. Both borings and surface observation demonstrate this to be true. One of the reasons for a built-up, or aggraded, condition is the extension of the stream by delta outgrowth or meander development. Any uncompensated lengthening that reduces gradient and competency disturbs the profile of equilibrium which has been established with respect to the average size of bed-load particles. In many meandering streams, the extension due to meander development is not compensated, and the result is upstream alluviation. To make this specific, assume a stream 90 miles long with a gradient of 2 feet per mile. The stream is just able to transport the average sized bottom material over this slope. If through delta extension, the length becomes 100 miles, the gradient is no longer 2 feet per mile but 1.8 feet per mile. This slope does not permit the sediment load to move as previously. Deposition therefore occurs upstream until the profile of equilibrium is re-established. Insofar as lengthen-

ing due to meander growth is not compensated by cut-offs, deposition also occurs to bring the stream up to grade

A loss of volume because of climatic change or diversion also causes deposition if the stream with reduced volume cannot transport its sediment load An interesting example of this is shown in the diversion of part of the water of the Mississippi through the Atchafalaya River, 190 miles upstream from New Orleans This natural diversion carries an estimated 500 000 second feet of Mississippi flood waters to the Gulf [10] The Mississippi has increased its slope by deposition as its volume has been diminished by the diversion, at the same time, the Atchatalaya has flattened its slope as its volume has been increased

In summary, the characteristics of maturity are an approximately graded profile, a broad, open cross section of flat floor, meanders, cut offs flood plains, and locally developed natural levees

*Old Age* Not only do the individual meanders shift position, but the whole meander belt itself is also subject to migration As a result, very extensive flood plains may develop Where the width of the flood plains is three or four times the width of the meander belt, the stream is characterized as *old* The extensive flood plains of old age show many meander scars, ox bow lakes which are remnants of cut offs, and ox bow swamps

Because of the fertile soils and flat topography of deltas and flood plains, these areas are usually well populated and very productive The streams related to these features, therefore are of particular economic significance Indeed, the well being and even existence of large populations depend in large measure on the behavior of these associated streams It is well, consequently, for the engineer to understand the fundamental characteristics of mature and old streams

*Rejuvenation* At any stage in the history of a stream, diastrophism may cause changes Uplift may bring the stream above grade

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[10] Salisbury E F, 'Influence of Diversion on the Mississippi and Atchafalaya Rivers, *Trans Am Soc Civil Engrs*, Vol 102 1937 p 75

and renew its downward cutting. Meanders then may become entrenched and valley flats left as terraces (Fig. 18-10). Lowering of the land relative to sea level may advance a stream in its cycle by reducing the amount of erosion the stream must perform to achieve grade or reach base level. Glaciation has rejuvenated the drainage of many areas by rearranging the stream, filling valleys, damming

FIG. 18-10. Terrace left by renewed downcutting of stream after uplift. Kennebec River, Maine.

old drainage ways, and causing streams to find new courses. Lava flows likewise may cause rejuvenation.

From the preceding discussion, it may be seen that, although subject to interruption, there is an orderly sequence of stream development, proceeding from initial gullies to youthful streams working above grade, through a mature stage in which a profile of approximate equilibrium has been reached, to the old-age stage of wide meandering on broad flood plains.

***Stream Types.*** Streams are classified in a variety of ways. Besides the classification according to the stage in the erosion cycle just given, supplementary classifications are in current use in which various types of streams are recognized. The two most significant types

for the purposes of the present discussion are the consequent stream and the subsequent stream.

*Consequent Streams.* Streams whose courses are determined by the initial surface slopes are termed *consequents* or *consequent streams.* The surface runoff from rains that fall on a newly uplifted ocean floor takes its way to the new shore in courses determined by initial slopes. Streams from inland, forced to cross a newly emerged bottomland, have the courses of their extensions similarly determined and are called *extended consequents.* Examples of this class of stream are abundant along the Atlantic seaboard on the coastal plain from Florida to Long Island.

*Subsequent Streams.* As stream work progresses, however, inequalities of erosion resistance may favor certain courses over others. Weak beds, faults or brecciated zones, and contacts in many places favor stream valley excavation. For the most part, these weak zones discovered and etched out by streams do not coincide in direction with the initial land slopes. The weak zones are discovered and eroded after, or subsequent to, the development of the consequent streams. These streams, adjusted to structural conditions and following weak zones, are called *subsequents,* or *subsequent streams.* Because subsequents do occupy structurally weak zones, for example limestone belts or fault zones, their recognition may be of practical significance.

## Drainage Patterns and Textures

The *drainage pattern* of an area is defined as the arrangement of the streams which drain it. The drainage *texture* refers to the spacing of the streams of an area. Both pattern and texture shed some light on the geology of many regions, for structure and rock resistance as well as initial slopes influence pattern and texture.

***Drainage Patterns.*** Drainage patterns have been named according to the general aspect or over-all impression created by inspection of drainage maps. The principal patterns are dendritic, trellis, angular, and radial.

*Dendritic Pattern.* A dendritic drainage pattern is one in which

the streams branch and rebranch in a manner similar to that of a hardwood tree. This pattern indicates a uniformity of rock resistance in horizontal direction, a uniformity that gives to no particular direction advantage over any other. Structural control therefore is absent. Streams that flow over horizontal sedimentary beds typically develop a dendritic pattern, as shown in Fig. 18-11 left. Granite and other crystalline rock terrains, also, may differ little over wide areas; the uniformity of resistance is commonly reflected in a dendritic drainage pattern.

*Trellis Pattern.* A trellis drainage pattern is one in which many of the streams are subparallel and the minor streams which join the parallel ones do so at approximately right angles. As shown in Fig. 18-11 center, a trellis effect is produced. In this pattern structural

FIG. 18-11. Drainage patterns: *left,* dendritic; *center,* trellis; *right,* angular

control is pronounced; folded or tilted beds, alternately weak and resistant, are safely inferred if the pattern is well developed.

*Angular Pattern.* The angular drainage pattern is one in which angular deflections of stream course are apparent as shown in Fig. 18-11 right; many of the streams are parallel. The pattern develops in rocks traversed by sets of joints or faults. Streams and their tributaries seek out the weak zones, and the sharp bends, parallel courses, and similar angles made by stream junctions are results of the structural control. The pattern somewhat resembles the trellis pattern.

*Radial Pattern.* A radial drainage pattern is one in which streams

flow outward in diverse directions from a central area, as spokes of a wheel radiate from the hub. Radial drainage commonly indicates a domal structure. Volcanic domes, laccoliths, stocks and small batholiths, and domally warped sediments are the principal structures that cause a radial drainage pattern.

***Drainage Texture.*** The spacing of valleys in an area, i.e., the texture of the drainage pattern, varies according to the climate, slope, and nature of the surface material. All three of these factors are reciprocally effective. Differences of texture, however, within a given climatic region, where slopes are known (topographic maps), can frequently be used to detect differences in lithology.

Studies of floods are assisted by analysis of drainage texture; the overland distance that surface runoff must travel before reaching a drainage way as well as land slope is of significance. The drainage texture, or density of pattern, can be expressed as a ratio between the total length of all drainage ways within the considered area and the total area considered. In compilation of data, based on some 340 drainage basins chiefly of the humid northeastern states, the ratios range from 0.89 to 3.37 miles per square mile.[11] The reciprocal of this ratio is the average distance between drainage ways.

*Climate.* The drainage texture, runoff factors being equal, is coarser in dry regions than in humid regions The close network of gullies in the semiarid badlands, however, indicates the importance of factors other than climate.

*Slope.* In general, the steeper the slopes the closer, or finer, the drainage texture. Table 18.4 shows variations of density ratios with land slope as derived from analysis of selected New England drainage basins.

*Surface.* Impervious surface rock increases erosive surface runoff. If the impervious cover is soft and easily eroded or gullied, the texture is close, and the topography is correspondingly dissected and rough. Clay soils in particular can be spotted from many maps of humid areas by the intricate pattern of close-textured drainage.

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[11] Langbein, W B., and others, "Topographic Characteristics of Drainage Basins," *U. S. Geological Survey Water-Supply Paper 968-C*, 1947, p. 133.

TABLE 18.4.* VARIATION OF STREAM DENSITY WITH LAND SLOPE

| *Range in Stream Density (miles per square mile)* | *Average Land Slope (feet per mile)* |
|---|---|
| 1.00 to 1.25 | 290 |
| 1.26 to 1.50 | 550 |
| 1.51 to 2.00 | 600 |
| 2.01 to 2.25 | 700 |

* From Langbein, *op. cit.*, p. 134.

## STREAM CONTROL

In March, 1913, a disastrous flood in the Miami Valley, Ohio, caused a loss of 360 lives and an estimated property damage of more than $100,000,000; adjacent areas were similarly devastated. As a result of the nationally aroused public interest and concern, the Miami Conservancy District was established and elsewhere flood prevention measures and flood studies accelerated. That continuing concern and effort are justified is shown by the fact that every year one area or another of the United States suffers financial and human losses because of floods. According to Weather Bureau data, floods cost the United States $2,108,000,000 in the period from 1902 to 1937, an annual mean of $59,000,000. In 1937, the loss was $432,-000,000. In July, 1951, floods of the Kansas, Osage, Neosho, Verdigris, and Missouri basins, according to a message to Congress[12] from the President of the United States, caused a flooding of 30-40,000 homes, with some 15,000 seriously damaged or destroyed, 20,000 people displaced, and 30,000 farms flooded with crop losses. The physical damage was estimated in this message at a billion dollars; the loss of income resulting was estimated at another billion.

The design, construction, or selection of flood-control measures lies in a specialized branch of engineering outside the province of the geologist. The following brief remarks on flood-control measures, however, will perhaps suffice to emphasize some geological principles that have been presented. The methods are: construction

[12] Truman, Harry, "Message to Congress," Aug. 21, 1951.

of levees, meander cut-offs, channel improvement, reservoirs, and diversion.

The formation of natural levees has already been indicated. At many places and for many years, increasing the height of natural levees has been the principal method of securing flood protection. Levees confine a stream to its channel and increase the velocity. This promotes scour in the leveed section and increases the efficiency of the stream above the leveed section because in alluvial material the increased gradient caused by the scour is rapidly distributed upstream. Any upstream improvements which increase the efficiency of the stream must be balanced by increased levee heights or other improvements downstream. Streams that normally aggrade their bottoms, levees, and flood plains tend to assume more and more unstable positions. At many places, adding to the heights of natural levees is an attempt to maintain an unstable condition rather than to improve it. Locally flooding of lands adjacent to a stream may do little damage. Weak places, or "fuse plugs," in levees at these locations permit the storage use of these areas to alleviate dangerously high floods.

Naturally occurring meander cut-offs have been described. Within recent years, man-made cut-offs have been constructed to straighten rivers and increase their efficiency. An interesting and significant series of cut-offs on the Mississippi River has recently been completed, as shown by Fig. 18-12. Because of the difficulty of comparing floods, it is too soon to state quantitatively how effective these have been, or what their effect has been on the regimen of the river. It would appear that good engineering practice calls for the maintenance of channels into the old meander loops that are cut off in this type of river improvement. By permitting part of the flood waters to pass around the old bends, some reservoir effect is secured and flood peaks are somewhat lowered.

Dredging to improve channels is necessarily practiced at many places, particularly where navigable channels must be maintained. Dredging, by itself, however, as a flood abatement measure is a never-ending and almost always losing struggle. Training walls and

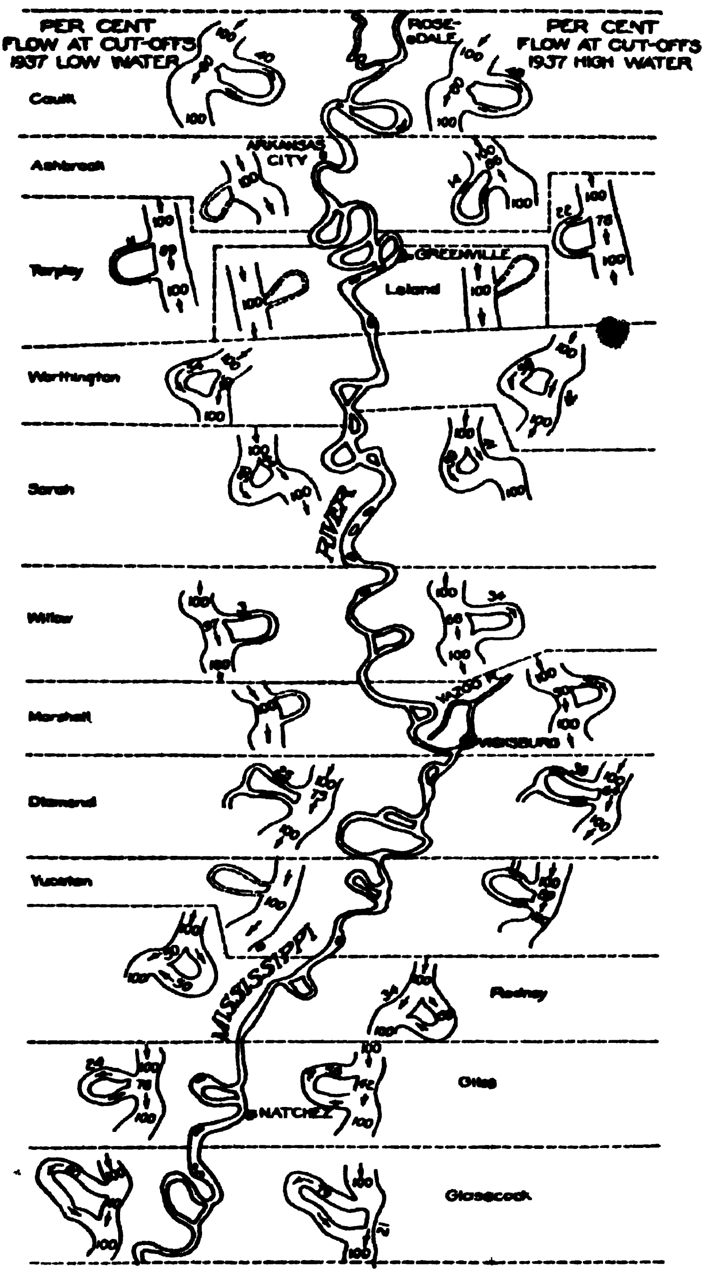


FIG. 18-12. Mississippi River cut-offs. (*Engineering News Record*)

Fig 18 13 A segment of the Missouri River before improvement

jetties are also channel improvement measures These structures direct the currents away from vulnerable banks and have been successfully used at some places to aid in maintaining channels (Figs 18-13 and 18-14).

Fig 18 14 Same segment as in Fig 18 13 after improvement (These photos by the U S Army Corps of Engineers appeared in *Civil Engineering*, 1946, accompanying an article by Col D B Freeman)

Reservoirs or retention basins contrast with the methods suggested in the preceding paragraphs which were directed toward increasing the efficiency of the stream and hastening the passage of flood waters downstream. Retarding or retention basins act in the opposite direction—they withhold water and regulate flows. In nature, lakes, swamps, and flood plains serve in this capacity. The St. Lawrence River, regulated by the storage basins of the Great Lakes, has only a 20 per cent greater maximum than minimum flow, whereas the Missouri River, not so regulated, has a maximum discharge over 2900 per cent greater than its minimum. Man-made reservoirs, however, are particularly adapted to the small streams; in small watersheds, especially those subject to sudden violent storms, reservoirs serve very effectively. But for most large streams, reservoirs are not practical. Six reservoirs in the headwater region of the Mississippi, with a storage capacity of 97 billion cubic feet, lose effect less than 100 miles below St. Paul. To prevent floods of the Mississippi in the vicinity of St. Louis or below, it would be necessary to have a retarding basin of some 5000 to 10,000 square miles in area, 10 to 20 feet deep.

Diversion as a flood control measure is for the most part of limited application. Although several notable diversions have been constructed in this country, they have served other purposes than that of flood control or abatement.

Diversion for flood control means simply opening up a new exit channel for a part of the stream flow. By such the velocity of flow just upstream of the diversion is increased because there is an increase of new channel capacity equal to the flow through the diversion channel. At the head of the diversion channel, velocity is decreased because of the divided flow. Tractive force is thus reduced by diversion below the diversion point, with probable choking of the channel by deposits as a result. The engineering problem is to plan the diversion in such a way that the capacity of the main channel is not choked up with sediment as a result of the diversion and flooding hazards are not thus made greater than before. At the same time, the

diversion channel likewise must have a regimen of balance between velocity and load supplied so that it will continue to be effective.

To date the most noteworthy attempt to abate flood heights by diversion is the Morganza Floodway, designed to steal 600,000 cfs of the Mississippi River water, and pass it through the Atchafalaya River into the Gulf of Mexico. This is controlled by a weir to divert the water from the Mississippi at the 55-foot flood stage. The degree of success of this structure in reducing flood damage below the diversion cannot yet be estimated.

From the brief remarks just made on the methods of flood control, but more especially from the preceding consideration of stream action and development, some of the complexities and difficulties of river engineering are apparent. Engineers are currently and will continue to be challenged by the problems of streams and in particular by the flood menace for years to come.

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# CHAPTER XIX

# DAM SITES AND RESERVOIRS

Dams must stand. Not all of them do, and there are all degrees of uncertainty about them. Reservoirs must hold water. Not all of them do, and there are many ways by which water may be lost. The work must be done safely as a construction job. Not all of them are, and there are many sources of danger. The whole structure must be permanent and the work has a right to be done within the original estimate. Not all of them are, and there are many reasons for their failure or excess cost, most of them geologic or of geologic dependence.[1]

ALTHOUGH THE GEOLOGICAL INVESTIGATION OF DAM SITES is usually delegated to a competent and experienced geologist, engineers engaged in dam work must have a thorough understanding of the geological principles involved in order to collaborate effectively in the geological investigations; to choose wisely between alternative sites, for although geologic conditions are only one group of factors which determine final choice of site, they are among the most significant; and in order to make best use of the geological findings in both design and construction.

The reasons for delegating the exploratory work to professional geologists are not far to seek. The failure of a large dam causes widespread disaster downstream, a disaster which may involve the property and lives of hundreds. The engineering staff and in particular the chief engineer are charged, therefore, with serious responsibilities. The geological problems of some locations are many and complex, requiring highly skilled professional analysis. It is prob-

[1] Berkey, C. P., "Responsibilities of the Geologist in Engineering Projects," *Tech. Paper 215*, A. I. M. E., 1929, pp. 8-9.

ably true today that most dam failures happen not because of faulty design of the structure itself but because of geological conditions which were not fully comprehended in advance. Thus, poor foundations and inadequate spillway provisions are responsible not only for failures, which fortunately are rare, but also for near failures and much excessive cost. Neglecting economic factors, probably the most adverse dam sites could be safely and successfully utilized through engineering skill and ingenuity *if sufficient advance information is available*. In addition to the preceding reasons for careful and competent studies of proposed sites, changes in the stream regimen that may be caused by regulation of its flow must be considered. Possible effects of water table changes about the dam, likewise, must be anticipated.

It is obvious, therefore, that as complete a knowledge as possible of the natural conditions prevailing at the dam site, including characteristics of the materials, the water table conditions, and the expected fluctuations of stream flow, must be assembled before design or construction. Alternative sites must be carefully sought, and the site finally chosen must represent a balance of economic factors among which geological conditions rank high. The most favorable sites have already been used or are being built upon. Construction in the future inevitably must meet increasing difficulties; precedent geological explorations must be thorough. But, however complete a geological report, to be of any value it must be used by engineers.

Because of the new exposures and more complete data available to the geologist during the construction, geological observations should continue during the construction period. This gives a check on previous inferences and often results in anticipation or appreciation of geological factors not disclosed in the preliminary exploration.

### Types and Purposes of Dams

Dams are barriers constructed to impound water for various purposes. The principal uses are to provide stream regulation and storage for community or industrial water supply, power, irrigation,

flood control, regulation of stream sediment load, and for inland water traffic. Although at the present time many multiple purpose dams are built, the diverse uses may be antagonistic. For example, a reservoir intended for use as a flood control measure should be nearly empty just preceding a flood, whereas a reservoir used to store water for power must yield a steady flow. If the two purposes are to be combined, the reservoir must have a capacity adequate for the storage of the flood waters in excess of the normal requirements for power. This calls for dams larger than required for either purpose by itself.

The principal classes of dams are earth or rock-fill and masonry. The choice of earth or rock-fill type depends upon foundation, sources of material, and always upon the economics of the project. In general, earth or rock-fill dams are used where the underlying material is too weak to support a masonry dam and the rock strong enough to support the load is too deep. If impervious rock at the dam site is not too deep and is strong enough to support a masonry structure, either a masonry dam or earth dam might be built. The choice would be a result of economic analysis. Earth dams are of all sizes; the largest one to date is the famous Ft. Peck, Wyoming dam, which is 4½ miles long, 4000 feet thick at the base, and 250 feet high. During its construction a slide involving some 5,000,000 cubic yards of emplaced earth took place.[2] Earth dams may be homogeneously impervious, or may have impervious cores or facings. Masonry dams require sound tight rock at an economically attainable depth. The principal types of concrete dams are *gravity, arch,* and *buttress.* Both earth and masonry dams require economic sources of suitable material for their construction.

### Geological Examination of Dam Sites

In the preliminary stages of a project, both reconnaissance and detailed surveys of dam sites are made. In the first place, preliminary or reconnaissance surveys determine the most favorable locations. Generally the preliminary survey narrows the choice within

[2] *Engineering News Record,* Vol 123, 1939. p. 681.

the considered area to relatively few sites. Following the reconnaissance, detailed surveys of the alternative sites are made to determine the final location and as quantitatively as possible the geologic conditions that will be encountered in construction.

***Preliminary Surveys.*** Topographic maps or aerial protographs establish the topographic areas or limits of exploration. The preliminary survey is aimed at the discovery of outstanding advantages or defects of topographically suitable locations. To this end are gathered data on lithology of both consolidated and unconsolidated rock, structure, physiography, and ground water.

*Lithology.* The identification of rock types exposed should be detailed enough to permit comparisons between the types at the various localities examined. Without detailed laboratory studies, relative strengths and permeabilities, nevertheless, can be estimated roughly; if detailed investigations of certain rock types or formations are needed, that fact can be established. Examination of thin sections of the rock types under the microscope aids in this part of the work, although much can be done megascopically. The degree and kind of weathering displayed, and the nature and origin of unconsolidated deposits, should be determined as far as consistent with the purpose of the reconnaissance. The lithologic investigations should indicate possible sources of construction material as well as foundation and abutment conditions.

*Structure.* Structural observations should include the major structural elements at each location and a determination of the modes of occurrence of the rocks. Joints, faults, foliation, and bedding should be noted carefully and the spacing and attitude of these structures should be recorded.

*Physiography.* The general physiographic features should be noted; shapes and types of valleys, gradients and stages of development are useful data. The physiographic evidence often helps in interpreting structure and lithology. Terraces, if present along the valleys, are often useful in establishing pertinent data relative to the project, since their origin, whether from uplift, meandering, structural control, glaciation, or landslide, is significant. In this stage

of the exploration, physiographic methods may indicate, at least relatively, expected depths to bedrock in the valley. An old-time rule-of-thumb method, based on the characteristic "V" cross-section of youthful stream valleys, has frequently given an approximation of the depth to bedrock beneath valley fills. By this method a projection of the bedrock slopes of the valley walls is taken as an approximation of the rock cross-section of the valley. Another method that may give an indication of depth to bedrock is a study of the gradients of the tributary streams. This is based on the principle that tributaries join the main stream at an accordant level; hence, if at a recent time the main stream was working at a lower level than at present, the gradients of the tributaries may indicate it. In the glaciated regions of the United States and Canada many buried or filled gorges exist. Because of the glacial derangement of drainage, many streams occupy preglacial valleys only in a part of their courses. It is obvious that physiographic observations may be of qualitative assistance during the reconnaissance.

*Ground Water.* Observations on ground water conditions are valuable. Springs, wells, both permanent and ephemeral streams, swamps, sink holes, solution cavities, or other evidences aid in establishing the water table and effects of ground water on the rocks of the region.

***Detailed Surveys.*** The rapidly made observations of the reconnaissance commonly bring to light defects disqualifying some of the sites. With further exploration therefore directed to the more favorable sites, the next step is to make detailed studies of these with the purpose of answering as specifically as possible the questions of suitability of the site. The primary questions are: Are there geological conditions that will affect the stability and success of the dam or that require special precautions during excavation and construction? Are the rocks strong enough and impermeable enough for a successful dam? What is the depth to bedrock?

***Lithologic and Structural Study.*** The preceding discussion has already indicated the general types of observations that should be made. At the sites selected for further study, commonly the first step

is to make a detailed surficial map. The lithologic types must be carefully mapped and studied in the field, and the thicknesses and succession of beds, flows, or minor intrusions determined. Samples should be taken for laboratory tests of strength and permeability and for the preparation of thin sections for microscopic study. The laboratory studies, supplementary to the field work, are of highest importance for some types of lithology, namely, the unconsolidated or the weakly consolidated sediments.

Coincident with the lithologic mapping and study, structures are mapped. Structural studies include mapping the attitude of beds, joints, faults, shear zones, and cleavage planes. The spacing and minor features of structures should be noted, insofar as they bear on the problem at hand. The weathering of the rock should be noted and the characteristics and localization of the weathered materials determined.

At this stage of the examination, preliminary cross-sections are drawn across the valley. The drawing of the cross-sections brings out clearly where more information is necessary. For whereas in much geologic work cross-sections are often based in large part on inference, engineering work requires that the work be checked and that the gaps filled in by inference must be so small as to leave no chance for major error.

After the surficial investigations, a drilling program can be planned to obtain supplementary geological data, and drill holes spotted which will yield the maximum information. Core drilling is the most satisfactory drilling method, and shot drilling is preferable to diamond drilling because of the sensitivity of the former in detecting open joints and cavities. Cores should be carefully preserved in their original sequence and accurate records kept of the drilling; especially should water losses be noted. Unfortunately, core recovery is highest for sound rock types and least for soft or fractured rock. Cracks and openings do not appear in the drill cores.

Water under pressure is often forced into exploration holes to obtain information on openings. Grouting of drill holes gives similar information. Grout should not be forced in under too high pres-

sures. Mead [8] estimates that about one pound of pressure per foot of depth is a safe maximum.

Large holes which can be drilled up to 36 inches or more in diameter are often used because they permit thorough inspection of the rock *in place*. The cores can be handled by bulldozer, Fig. 19-1. Locally, because water entering the hole makes trouble, small-

Fig. 19-1. Cores of dolomite extracted from the 36-inch calyx core drill holes at Norris Dam. (Ingersoll-Rand)

diameter holes are drilled and grouted either inside or outside the area of the large hole before the latter is put down. If this is done, the engineer or geologist lowered into the hole can examine not only the rock but also the action and penetration of the grout.

A systematic search for suitable construction material for the dam is an important part of the survey. Because of the large volumes required for many projects, excessive haulage or import of material

[8] Mead, W. J., "Geology of Dam Sites in Hard Rock," *Civil Engineering*, Vol. 7, 1937, p. 331.

might be prohibitively expensive. If necessary, quarry sites should be chosen as sources for crushed stone. The engineer must know locations of material sources, and also their qualities and volumes.

*Geological Characteristics of Foundations and Abutments.* The physical characteristics of the foundation and abutment rock must be carefully determined. A very concise and able summary of these characteristics has been given by Warren J. Mead.[4] Particular attention should be paid to those factors which bear on the success of the dam. The strength of the rock, its structure and permeability are the important items. For purposes of the discussion which follows, rocks can be divided into five main groups: the strong massive rocks, cavernous rocks, thin-bedded sediments, weak rocks, and the unconsolidated rocks.

*Strong massive rocks.* Dam sites underlain by fresh igneous intrusives, granite, monzonite, syenite, gabbro, and other varieties are strong enough to support any load imposed upon them. The problem is to determine possible avenues of excessive percolation. Shatter or shear zones may be present; often the structurally weak zones are marked by decomposed rock. Joint systems may be sufficiently open in the surface zone to require grouting. The fresh rock surfaces of these types bond well with concrete and require no special treatment.

In this category of foundation and abutment materials are included also thick massive lava flows. Many lava flows are complexly jointed; it may be necessary therefore to excavate and grout a portion that permits too ready circulation. Some flows are scoriaceous, or vesiculated. If the vesicules have been plugged with mineral matter, the rock is satisfactory. Vesiculation should be carefully noted in the study of volcanics.

Included also in this category of strong rocks are the gneisses, schists, phyllites, slates, and quartzites if in a fresh condition. These rocks, as the igneous rocks just discussed, are strong enough to support great loads and the principal question is to determine whether or not structural zones are present along which percolation may be excessive. Faults and shear zones may be discovered, and fracture

[4] *Ibid.*, pp. 331-334; 392-395.

cleavage often localized in thin zones may require special attention. The fresh surfaces of these rocks give a good bond with concrete and require no special treatment other than cleaning.

Whether or not conglomerates, breccias, and sandstones are also included in this category of strong massive rocks depends upon the degree and character of cementation. The common cementing agents are calcite, silica, iron oxide, and fine clastics. If the rocks are thoroughly cemented by quartz, calcite, or other mineral cement, or by thoroughly indurated clastic cement, they have adequate bearing capacity for the heaviest loads. If they are cemented with fine clastic sediment, clay, or mud, care should be taken to determine whether or not they will soften on prolonged contact with water under pressure. If the rocks of this group are only partially cemented with calcite or silica, their bearing strength may be adequate, but they may be excessively permeable. Shaly or argillaceous layers or seams in these rocks should be given careful attention since slips might occur along them.

*The cavernous rocks.* As was noted in the discussion of groundwater movements, two types of rock are excessively permeable at many places because of the presence of cavernous openings. These are the carbonate rocks and vesicular or scoriaceous lavas.

Limestones, dolomites, and their metamorphic equivalents, the marbles, are the only common rocks that are excessively dissolved by subsurface water. These carbonates frequently have cavernous structures and solution channels which allow free circulation of water (Fig. 19-2). In the study of carbonate rocks, therefore, care should be taken to determine whether or not solution openings are present; they are always suspect. Neglect on this score gave rise to an expensive object lesson in dam site studies, the Hale's Bar Dam of the Tennessee River.[5] During the excavation for this dam so many solution cavities were encountered that completion of the dam was long delayed and costs were excessive. About 5000 tons of cement were used in grouting open cavities. After the dam was in use, it leaked too much. Ten years after completion, and after a

[5] *Engineering News Record,* Vol. 96, 1926, p 798

varied program of unsuccessful attempts at remedy, leakage was finally reduced to an acceptable rate by introducing hot asphalt into a large number of drill holes. More than 11,000 barrels of asphalt were used.

Limestone, dolomites, and marbles commonly weather into clay as a result of the accumulation of insoluble clay sized impurities which were present in the original sedimentary deposit. At most places, there is a rather sharp break between the weathered and un-

FIG. 19-2. Leaky and cavernous limestone at the Great Falls Dam Site, Caney Fork River, Tennessee.

weathered rock. Beneath the weathered mantle, the surface of the bedrock is often highly irregular. This condition of surface adds considerably to the labor of preparing it for a large structure. Well-consolidated carbonate rocks have a good bearing capacity except where too cavernous. They bond well with concrete.

Scoriaceous lavas are here classed with the cavernous rocks, for although the cavernous openings may not be large, the rock is often excessively permeable. Both top and bottom contacts of flows should be carefully appraised, for in addition to vesiculation cavities, which are commonly localized in the upper parts of flows, irregular cavities

at the contacts of two flows or at the basal contact of lava that has flowed over other rock types are very common.

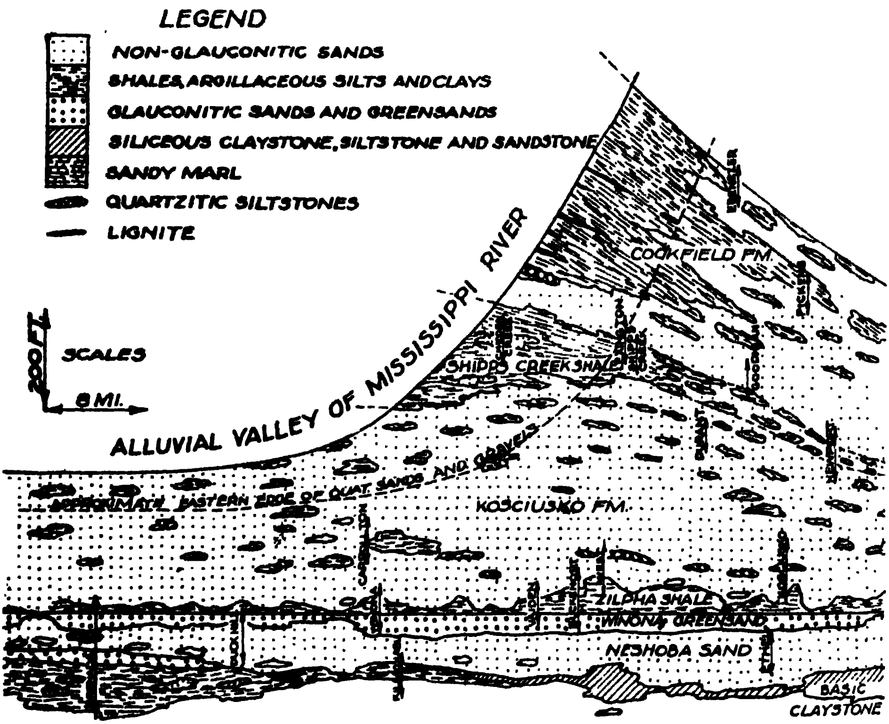
*Thin-bedded sediments.* In many regions, sedimentary beds vary rapidly in vertical section. Shales, sandstones, and limestones are found intercalated in a succession of thin beds. Many individual beds measure from less than an inch to a few inches in thickness. An example of lithologic variation, both vertical and horizontal, is shown in Fig. 19-4, from the Mississippi Geological Survey. Care

FIG. 19-3. The same view as Fig. 19-2 after final grouting with asphalt and cement. (Photos courtesy of TVA and B. C. Moneymaker)

must be taken to determine the characteristics of the beds, particularly after prolonged soaking. The coarse textured layers and limestones may be too permeable. Whereas the bearing strength of the series may be found adequate, the possibility of sliding along bedding planes or joints caused by downstream thrust of the dam should be considered. Weak shaly or clayey layers dipping at low angles downstream may serve as slip surfaces. At some places it is necessary to strip off a shaly bed to get a good bonding surface for concrete structures. Elastic deformation of the foundation under the proposed

load should be anticipated from tests and allowed for in design if necessary.

*The weak rocks.* Claystones and volcanic tuffs are representative types of weak rocks. If argillaceous rocks have closely spaced parting planes parallel to the bedding or lamination, they are called *shales.*




*Miss. Geol. Survey*

FIG. 19-4. Geological cross section showing lateral and vertical variations of material.

Mead[6] recognizes two types of shales: those that have been consolidated by compaction under load, but with little or no cementation; and the cemented type, which in addition to compaction have become cemented or "set up." There are, of course, all gradations between these types. The compaction shales and some volcanic tuffs tend to slake. Poorly cemented argillaceous sandstones and con

[6] Mead, W. J., *op. cit.*, p. 392.

glomerates also share this tendency In the dry state many rocks consolidated by compaction give good strength tests and appear adequately strong. After soaking, however, many are found to be too weak to support heavy loads. The San Francisquito Dam failure, California, illustrates this point. This dam, completed in 1926 to create auxiliary water storage for the City of Los Angeles, was of the gravity type, 700 feet long and 200 feet high Part of the dam rested on schist and part on an argillaceous conglomerate with thin sandy and clayey interbeds. The contact between the two formations is a fault along which no apparent movements have taken place in recent times. When placed in water, the conglomerate slakes down to a weak mass. Wet tests apparently were not made, however, prior to construction. Two years after the completion of the dam, when the reservoir was finally filled, leakage through the conglomerate occurred and the dam failed disastrously.

The cemented shales have greater bearing strength than the compaction shales and are less likely to fail by flowage. Many are weak in shearing resistance, and many are relatively elastic. Elastic deformation under large load is a possibility that should be explored in advance of design and allowed for if tests show that it must be anticipated.

If concrete is to be placed on compaction shales, every precaution should be taken to prevent drying out of the prepared surface, as little time as possible should elapse between preparation and pouring the concrete. Otherwise, the partially dried surface layer tends to slake into mud at the base of the concrete. The surfaces of cemented shales need no special preparation other than removal of weathered or decomposed material.

*Unconsolidated rock.* Many dams are built on unconsolidated material. Coarse sand and gravel, although permeable, have good bearing strength. The silt deposits of most flood plains are loosely packed; hence adequate provision must be made for drainage in order to prevent plastic deformation. Many shales are compactible. If the water cannot escape rapidly enough to meet the demands of loading and compaction, it must carry part of the stress and in so

doing endangers the stability of the foundation. The fine sands and silts of river deposition offer some of the most difficult problems of foundation engineering. Clays are inherently plastic and constitute dangerous foundations. The bearing strength of clays should be carefully investigated at every location where heavy loads are to be superimposed.

If the permeability of the underlying material is greater than allowable, sheet-piling or other devices are installed and an impervious apron carried upstream. The object of these devices is to increase the distance the water must travel through the permeable material under the dam so that its velocity is reduced to a safe figure Bryan[7] estimated that the percolation factor, which is the ratio of length of travel of the water through the pervious material to the height of water behind the dam, ranges from five to six for gravel to twenty in open-packed sand, in successful dams. If the materials were homogeneous throughout the cross-section of the valley beneath the dam, the percolation factor could be worked out exactly. However, because of the heterogeneity of materials and variations in permeability, approximations only are possible, and a generous safety factor is advisable.

*Depth to Bedrock.* The accurate determination of the rock profile along the axis of the dam is called for. If bedrock is not exposed continuously along the section, its depth must be inferred within close limits of accuracy from data furnished by properly placed test pits, trenches, rod soundings, drill holes, or by geophysical exploration. The principal role of the geologist in this exploration is to locate those places where the most information at the least expense can be obtained that will serve the purpose. At many places, the geological examination will reveal areas that might be overlooked in an undirected exploration program where supplementary information is necessary. An illustration of this point is one sand and gravel-filled stream gorge more than 100 feet deep and less than 50

[7] Bryan, Kirk, "Problems Involved in the Geologic Examination of Sites for Dams," *Tech. Pub. No. 215*, A. I. M. E., 1929, p. 16.

feet wide which was discovered after the design was completed, contracts let, and construction of the dam under way.

*Test pits and trenches.* Test pits and trenches are limited to places where the overburden is relatively thin. Although this method of exploration is frequently overlooked in dam site exploration, it is an excellent practice where feasible, even with the help of cribbing or timbering, for the bedrock can be examined in place.

*Rod soundings.* Rapid determination of the thickness of the unconsolidated material is frequently made by the driving of steel sounding rods. The drawbacks of the method are that the character of the material penetrated can only be guessed at, and boulders may be mistaken for bedrock. For these reasons the use of sounding rods is of limited value.

*Drill holes.* Although progress has been made in consolidation or freezing of unconsolidated material to permit core drilling, augering or wash boring is the general practice. The drill samples should be saved for examination. Pulverized samples are of limited value, however, as they incompletely represent the material penetrated. Care should be taken to penetrate bedrock far enough to insure that a boulder has not been mistaken for ledge. In wash boring, this means a change of drilling method or relocation of the hole.

*Geophysical methods.* The determination of depth to bedrock has been successfully made in recent years at many places by the application of geophysical methods of exploration; and it is probable that these methods will be increasingly useful and used in engineering practice. A brief discussion of geophysical methods is given in Chapter XII.

## Reservoirs

More than one dam has been built subsequently to be abandoned because the reservoir proved to be excessively leaky. The reservoir basin must have an effective storage capacity. Excessive silting has reduced or nullified the value of many dams. A useless dam is a monument to the builders, but has little other value except perhaps that of an object lesson to professional colleagues. Studies of reser-

voir sites, therefore, are directed to consideration of probable water losses and to probable silting.

***Water Tightness.*** The degree of water tightness necessary to a successful reservoir varies. Dams built for flood control may be effective even if the reservoir is very leaky. The seasonal distribution of precipitation and run-off is also to be considered. A highly leaky reservoir may be satisfactory in an area where run-off is evenly distributed throughout the year, whereas a reservoir basin with the

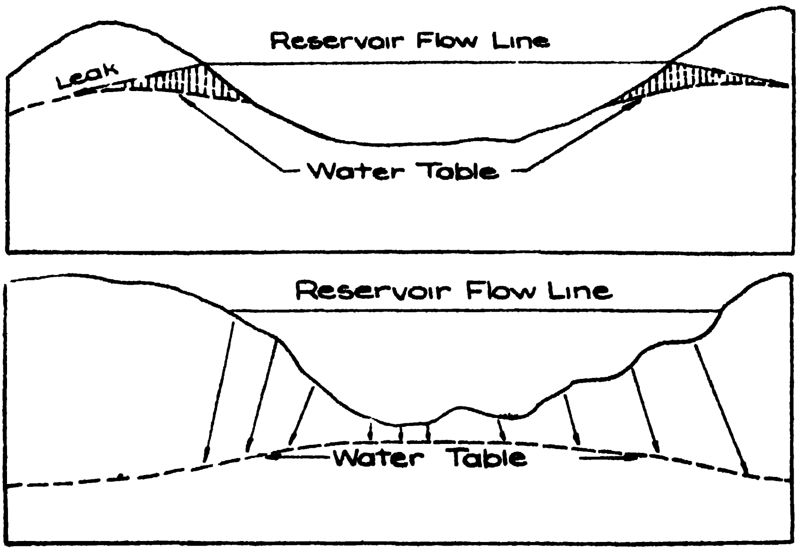



FIG. 19-5. Reservoir leaks because of water table position.

same rate of water loss may be of little value in an area where runoff is seasonally deficient.

What has been said of permeable rock types in preceding sections does not need to be repeated here. A low water table in cavernous limestone, vesicular lavas, or coarsely granular materials constitutes a hazard to maintenance of the desired flow line in the reservoir (Fig. 19-5). Although leaky foundations and abutments may be made sufficiently watertight by grouting, a leaky reservoir of much volume cannot be grouted economically. Natural clogging of openings by sedimentation, however, may diminish leakage over a period of time.

The construction of a dam raises the water table behind it. If

the flow line of the reservoir overtops the ground water divide between the reservoir and an adjacent depression of the water table, leakage may be expected, as is shown in Fig. 19-5B.

***The Silt Problem.*** If sedimentation continues at the present rate, one fifth of the nation's water supply reservoirs will be useless within fifty years. It is further estimated that within a century more than half of them will be so silt-filled as to be useless. Table 19.1 shows the results of just one series of floods in the spring of 1938 on some of the small reservoirs of Los Angeles County

TABLE 19.1.* LOSS OF RESERVOIR CAPACITY, LOS ANGELES COUNTY, SPRING 1938

| *Reservoir* | *Loss of Capacity (acre-feet)*† | *Capacity Lost (%)* |
|---|---|---|
| Pacoima | 500 | 8.9 |
| Big Tujunga | 1520 | 24.4 |
| Devil's Gate | 984 | 24.6 |
| Big Santa Anita | 327 | 32.2 |
| Puddingstone Division | 78 | 64.5 |
| San Gabriel No. 1 | 5202 | 9.7 |

* *Engineering News Record,* Vol. 122, 1939, p. 16

† 1 acre-foot = 43,560 cubic feet.

The costs of sluicing operations carried on in the same county during 1941-1943 are shown in Table 19.2.

TABLE 19.2.* SLUICING OPERATIONS, LOS ANGELES COUNTY, 1941-43

| Reservoir | Stream Flow (acre-feet) | Est. Debris Moved (cubic yards) | Total Expenditures | Cost per Cubic Yard |
|---|---|---|---|---|
| Big Tujunga | 7597 | 907,200 | $5,256.01 | $0.0058 |
| Eaton | 1100 | 66,150 | 323.50 | 0.0049 |
| Devil's Gate | 11,037 | 1,135,930 | 3113.98 | 0.0027 |
| Sawpit | 956 | 199,240 | 4850.46 | 0.0244 |
| Sierra Madre | 1744 | 48,390 | 1800.34 | 0.0370 |
| Big Santa Anita | 966 | 235,390 | 1825.88 | 0.0078 |
| San Gabriel No. 2 | 702 | 169,880 | 5594.58 | 0.0330 |

* *Engineering News Record,* Vol. 132, 1944, p. 42.

Data on the silting of larger reservoirs, as measured over periods of years, are given in Table 19.3. These data indicate the magnitude of the silt problem in several parts of the United States. On the basis of economic studies, the United States Department of Agriculture[8] estimates that the silt damage done to reservoirs in the United States is not less than $10,000,000 a year and may be as high as $50,000,000 a year. As J. C. Stevens[9] said: "It is unfair to sit smugly complacent and to pass this problem flippantly on to future generations. The engineer should be equal to the task of finding a solution, but it will take many years of experimentation and study, and he should be at the task. . . ." Examples of damaging sedimentation in reservoirs and of engineering comment on the significance of the silt problem could be multiplied. The illustrations given are introduced simply to point out that the silt problem does arise in the selection of dam and reservoir sites and that, although seldom a decisive location influence, simple economics requires its consideration. At present, there is no economical method of desilting a large reservoir. Once capacity is reduced to less than the necessary minimum, new dam sites must be sought.

*Transportation of Silt in Reservoir Basins.* The transportation of silt by streams and its deposition along the course of travel have already been discussed. The mechanism of silt transportation in reservoirs (and lakes), however, is somewhat different from that of streams and only recently has attention been called to the principles involved.

Where a stream enters a lake, its velocity is checked, and coarse particles are deposited; thus deltas are built. The gradually diminishing velocity of the stream current as it penetrates the lake causes a gradation of coarse to fine sediments towards the deeper water. At times, streams entering lakes may be highly charged with suspended sediment. Floods of the main stream or of some tributary account for changes of suspended sediment load. The bulk specific gravity

[8] Brown, C. B., "The Control of Reservoir Silting," *U. S. Department of Agriculture Miscellaneous Pub. No. 521*, 1944, p. 21.

[9] Stevens, J. C., "The Silt Problem," *Am. Soc. Civil Engineers, Trans.*, Vol 101 1936, p. 209.

TABLE 19.3.* RESERVOIR SILTING

| Reservoir | Stream | Drainage Area (square miles) | Original Capacity (acre-feet) | Period (years) | Annual Loss of Original Capacity % |
|---|---|---|---|---|---|
| Elephant Butte | Rio Grande, N. M. | 30,000 | 2,640,000 | 8.67 | 0.8 |
| Roosevelt | Salt, Ariz. | 5670 | 1,370,000 | 20 | 0.36 |
| Keokuk | Mississippi | 119,000 | 370,000 | 15 | 2.0 |
| Hales Bar | Tennessee, Tenn. | 21,800 | 156,000 | 16.92 | 1.7 |
| Guernsey | North Platte, Wyo | 16,200 | 72,000 | 5.9 | 1 98 |
| Old Lake Austin | Colorado of Texas | 38,200 | 49,300 | 6.75 | 7 09 |
| Boysen | Bighorn, Wyo. | 7740 | 16,000 | 13 | 6 2 |
| Sterling Pool | Rock River, Ill. | 8760 | 13,700 | 18 | 0 8 |
| Coon Rapids Pond | Mississippi, Minn. | 19,000 | 8000 | 16 | 1.07 |

* Data from Stevens, J. C., *Trans. A. S C. E*, Vol. 101, 1936, p. 210.

of roily water which enters a lake or reservoir is higher than that of clear water; consequently, the roily entering water plunges beneath the slightly lighter, clear water and becomes a turbid density current (Fig. 19-6). As Bell [10] states it: "In ordinary streams, water propels suspended sediment. In turbid density currents, sediment propels the water." The difference in density between clear water in the lake or reservoir and the turbid water entering supplies the driving force to maintain the underflow. Turbid underflows are

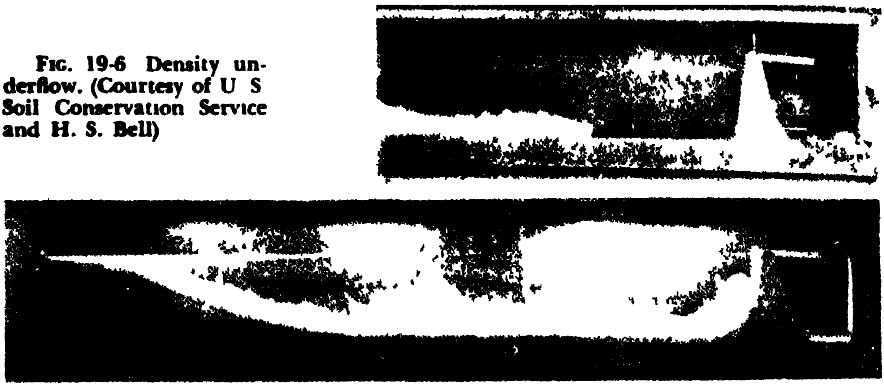


FIG. 19-6 Density underflow. (Courtesy of U S Soil Conservation Service and H. S. Bell)

comparable to similar but perhaps more widely known density flows, seen as dust storms and cold fronts.

Density differences of only a few hundredths of one per cent are sufficient to maintain separate identities of the differing water masses where turbulence and currents are slight. In quiet waters, the contacts or interfaces of the flows remain remarkably abrupt with little mixing of the fluids. Experiments [11] have shown that the ratios of effective densities of underflowing liquids to those of overlying liquids, i.e.,

$$\frac{\text{Weight per unit volume of underflowing liquid}}{\text{Weight per unit volume of overlying liquid}}$$

[10] Bell, H. S., "Density Currents as Agents for Transporting Sediments," *Jour Geol*, Vol. 50, 1942, p. 518.

[11] Bell, H. S., "Stratified Flow in Reservoirs and Its Use in Prevention of Silting," *Miscell. Pub. No. 491*, U. S. Department of Agriculture, 1942, p. 6.

necessary to develop density flows may be very small. In the laboratory, for example, a ratio as low as 1.0001 has produced underflows. The slope of the reservoir or lake bottom over which underflows take place also may be very slight. In laboratory experiments,[12] slopes as low as 0.25 per cent have been used.

At Lake Mead—the lake created by Hoover Dam—turbid density flows travel the full length of the reservoir, more than 100 miles, and are checked by the dam. Bell [13] estimates from data gathered by the United States Geological Survey and the United States Bureau of Reclamation that more than 232,000,000 tons of sediment were deposited in Lake Mead between closing of the diversion tunnel in 1936 and June 1941; deposition at the rate of approximately 875,000 tons per week. He states: ". . . it seems reasonably certain that, with proper outlet facilities, from 75 to 90 percent of this sediment could have been carried beyond the dam by the use of stratified flow." [14] About 4 billion tons of silt had been deposited in Lake Mead within 24 years after the completion of the dam, a daily average of some 400,000 tons.

*Silt Load of Streams.* A number of factors enter into a consideration of the silt contributions to a lake or reservoir by its inflowing streams. Among the more important might be mentioned the climate and vegetation, rock types, and human use of the lands through which contributing streams pass.

It is a matter of common observation that in the more humid regions more or less permanently clothed with vegetation, the streams tend to run clear. A comparison of the Missouri and Ohio Rivers helps make this clear, although of course the vegetational and climatic differences of the terrains drained by these two tributaries of the Mississippi are not the sole reasons for differences in suspended loads. The Missouri River, with a drainage area estimated at 528,000 square miles, discharges (average) approximately 64,000 second-feet; the Ohio River, with a drainage area of some 203,000 square miles,

[12] *Ibid.*
[13] *Op. cit.*, p. 42.
[14] *Op. cit.*, p. 43.

discharges (average) approximately 239,600 second-feet. During a six months' observation period, the Missouri was estimated to carry about 47,000,000 tons of suspended silt; in a comparable five and a half months' observation period the Ohio was estimated to carry 375,000 tons of suspended silt.

The rock types through which a stream and its tributaries flow are also factors in the silt loads. Crystalline rock areas yield relatively little silt as compared with those composed of weakly cemented argillaceous sandstones, siltstones, and sandy shales. The works of man in the drainage basin are also important. Poor cultivation practices, overgrazing, improper disposal of mine waste, and other works of man accelerate erosion or contribute directly to stream loads.

*Methods of Silt Control.* Various approaches to the control of reservoir silting have been made. In general these include reservoir design, and installation of outlets, check dams and settling basins upstream from the reservoir, by-passes and watershed improvements.

Although often neglected, the ratio of size of the drainage basin to storage capacity of the reservoir has long been recognized to be critical. Deficiency of data account for certain failures to establish a satisfactory ratio; however, regional data can generally be obtained and satisfactorily applied. Reservoirs of the southeastern states with storage capacities of less than 75 acre-feet per square mile of drainage area or reservoirs of the Texas-Oklahoma region with storage capacities of less than 250 acre-feet per square mile of drainage area are subject to silting at rates of economic concern.[16]

A comparison of the silting rates of two Texas water supply reservoirs illustrates this point. Lake Waco, with a drainage area of 1662 square miles, was designed to have an original capacity of 39,378 acre-feet, or 24 acre-feet per square mile. Lake Bridgeport, above Fort Worth, with a drainage area of 1051 square miles, was designed to have an original capacity of 292,000 acre-feet, or 278 acre-feet per square mile. In each the rate of sedimentation has been about 0.8 acre-foot per square mile of drainage basin: in the Waco Reservoir

[16] Brown, C. B., "The Control of Reservoir Silting," *Miscell. Publication No. 52*' U. S. Department of Agriculture, 1943, p. 27.

this amounts annually to a loss of 3.34 per cent of its original capacity; in the Bridgeport Reservoir to 0.27 per cent annually.[17]

Outlet works have been designed for some dams to pass much of the especially silty water downstream. An old example is offered by the Aswan Dam on the Nile River; there at the beginning of the flood period the gates are open, and the heavily silt-charged water

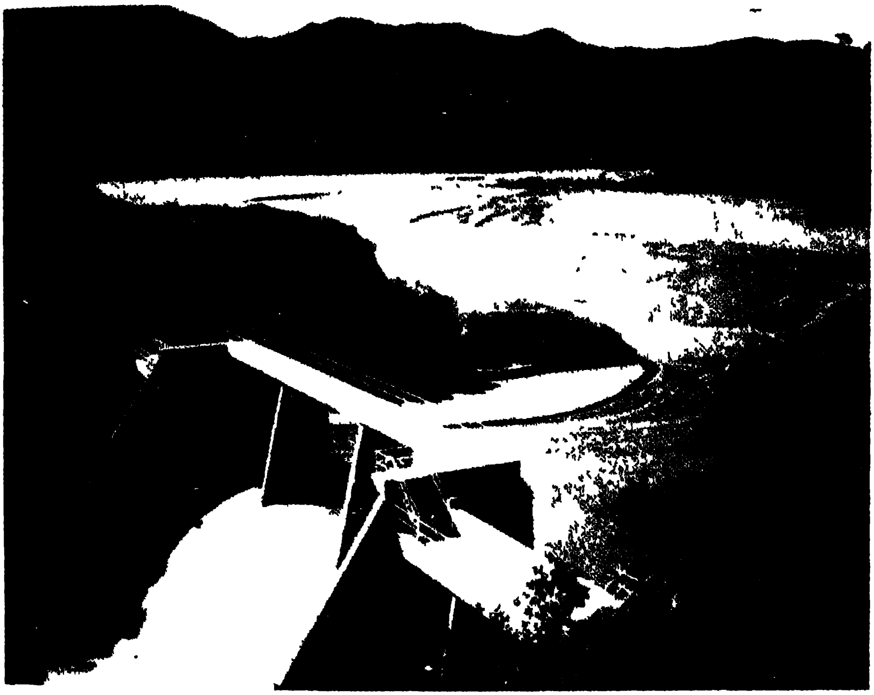


FIG 19-7. Sedimentation behind the Mono Creek Dam, California (U. S. Forest Service)

flows through unimpeded. At other places, the Zuni Dam, New Mexico, for example, sluice gates have been installed which are partially effective. Recently, appreciation of the role of density flows in reservoir silting has led to studies of designs that will permit advantage to be taken of this mechanism of silt transportation. Many data have yet to be accumulated, however, before generally applicable principles of design can be developed.

[17] *Ibid.*

Small check dams across tributaries which contribute excessive amounts of sediment to the main stream have been built at many places. These constitute settling basins or silt traps. Sedimentation or settling basins, also, have been effectively constructed along the channel or off the channel of the major streams. Most of these structures, of course, are temporary and must therefore be of economical

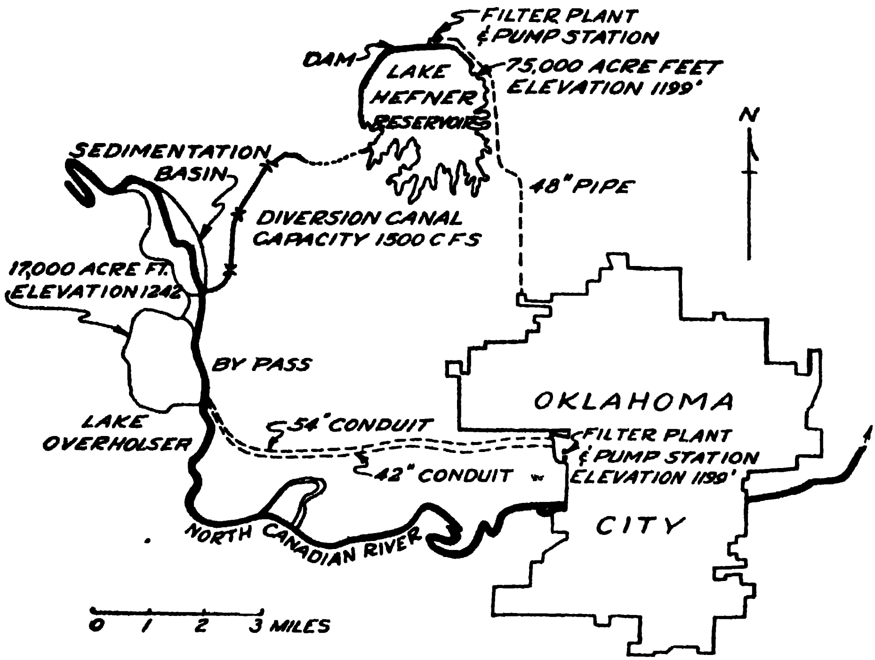



FIG 19 8 Lake Overholser, Oklahoma City, Oklahoma (Courtesy of H F Chase, City Engineer)

construction. If they are really effective, they must be cleaned out or relocated within relatively short times. Fig. 19-7 illustrates a concrete check or debris dam built on Mono Creek, California; this reinforced concrete structure stands 35 feet above the level of the creek and is 192 feet long. In the 1936-1938 period, its basin was completely filled with coarse sediment.[18]

Diversion of sediment-laden waters around the reservoir is also

[18] Brown, C. B., *op. cit.*, p. 35.

a method locally used to diminish reservoir silting. One of the most notable of these in the United States is the bypass canal at Lake Overholser, a water supply reservoir for Oklahoma City. This canal and the sedimentation basin associated, shown in Fig. 19-8, are estimated to have kept 93 per cent of the stream sediment out of the reservoir.[19]

The improvement of agricultural practices and adoption of soil-conservation measures within a drainage basin form another approach to the silt problem. The problems of soil conservation, floods, and silting are all interrelated.

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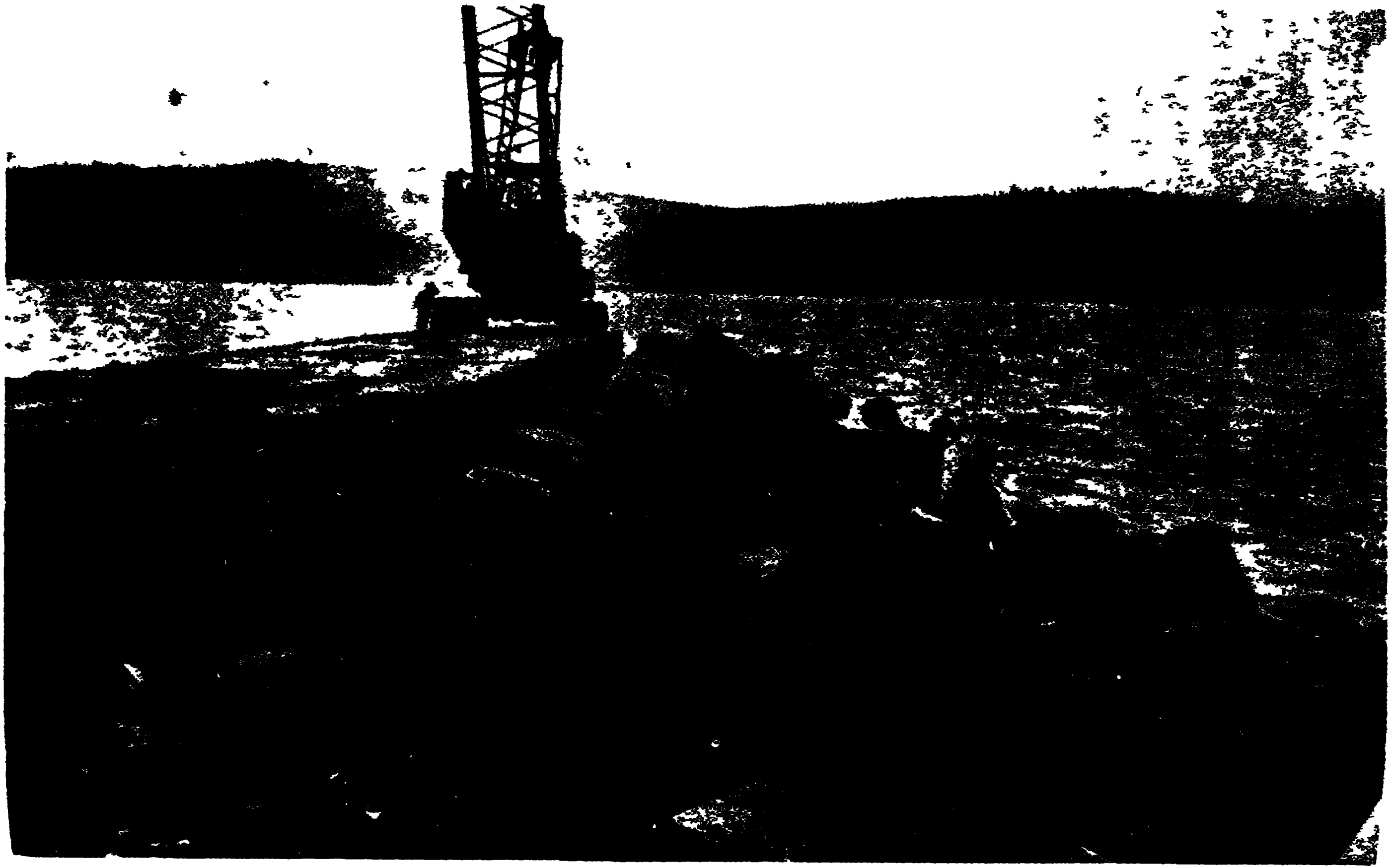
Stevens, J. C., "The Silt Problem," *Trans. Am. Soc. Civil Engrs.*, Vol. 101, 1936, pp. 207-288, with discussions by other engineers.

[19] *Ibid.*, p. 61.



Courtesy of California Div of Mines

Concrete Tetrapods Used in Shore Protection

CHAPTER XX

# SHORELINES

THE TENS OF THOUSANDS OF MILES OF SHORELINE, BOTH sea and lake, give rise to a variety of engineering problems. At places are found sandy beaches, some are stable, but many are undergoing rapid alteration. Elsewhere are found rocky shores; but even these locally give way before the onslaught of waves. Engineering structures to prevent losses by erosion, to control deposition, to stabilize or improve existing conditions, to maintain or to create shore and harbor facilities call for engineering skill and ingenuity based on knowledge of the underlying geological principles.

FIG. 20-1. Wave damage to shore and highway, Sunset Cliffs, California. (Courtesy of F. P. Shepard)

Many striking examples of shore changes could be given to illustrate both the magnitude of local alteration and the impressive

power of wave and storm. The island of Helgoland, in the North Sea, has shrunk under wave attack from a circumference of about 120 miles (A.D. 800) to a circumference of less than 3 miles. Parts of the Yorkshire coast have receded more than a mile since the Norman Invasion in 1066, and at many places on this coast the rate of cliff recession is on the order of 5 to 15 feet per year. Currently parts of the New Jersey coast are receding at a rate estimated at 5 feet per year, and parts of the Florida coast are yielding at about the same rate. Along wasting shores, thousands of structures necessarily have been set back or protected, or have been destroyed Fig. 20-1 illustrates the point. Many hundreds of specific examples could be marshalled.

The following discussion treats marine coasts and sea work Most of the discussion, however, applies as well to lakes and lake shores, and the latter, therefore, are not accorded separate treatment

## The Margins of the Seas

Nearly three-quarters of the earth's surface is covered by the seas. Although formerly thought to be monotonous plains, the topographic diversity of the sea floors has been demonstrated by recent soundings to be fully comparable with that of the continents Deeps extend downward more than 6 miles beneath the sea surface,

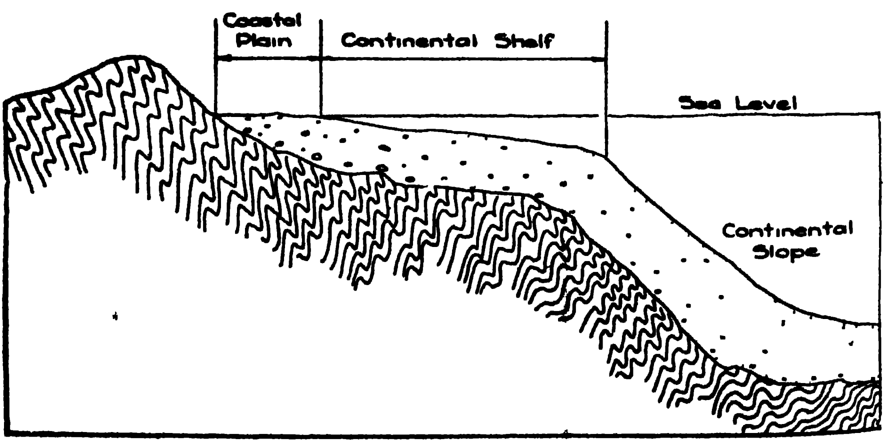



Fig. 20-2. Continental shelf and continental slope.

mountain chains rise above the floors of the seas, and some of them emerge above the surface to form island arcs; volcanoes rise above the sea floor, and many of them rise high above the sea level.

Most of the seas are margined by shallow water zones, called the *continental shelves,* bordering the continents. These, which are of varying widths, slope gently seaward from the land masses until, at depths averaging about 100 fathoms, the slopes leading down into the deep sea basins abruptly increase. The relations are shown in Fig. 20-2. At many places the continental shelves are cut by great gorges or canyons several thousands of feet deep. At other places shoals are known. If the irregularities of the continental shelf are truly the results of stream sculpture, very important changes of sea level are indicated. Marine sediments found on the lands, both of recent and of very ancient deposition, bear witness to shoreline migrations of far-reaching extent. The continental slopes are the true margins of the continental masses. The ocean basins are at present slightly over-full and flood the continental margins or continental shelves.

The engineer, however, is principally concerned with the shore zone and shoal waters which margin it. Fig. 20-3 illustrates many of the terms used. Primarily, present-day shore changes are due to water in motion. An engineering analysis of shores, therefore, in-

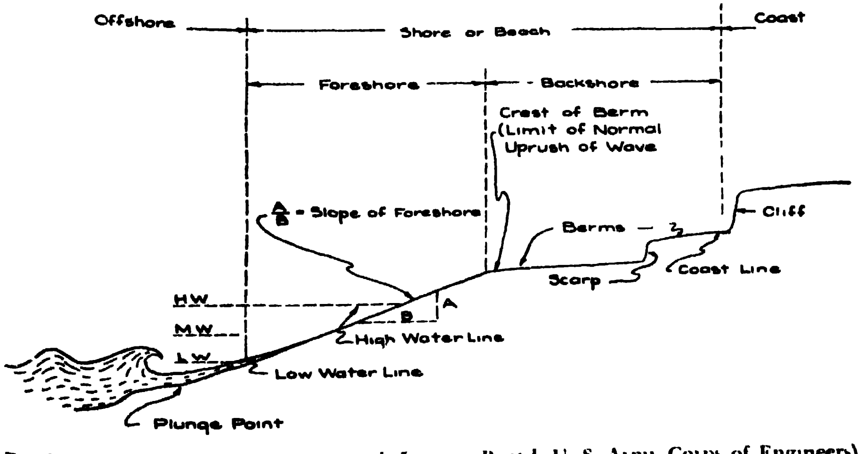



FIG. 20-3. Coast and shore zone. (Beach Erosion Board, U. S. Army Corps of Engineers)

cludes physiographic studies, offshore and onshore profiles; the directions, frequencies, and maxima of winds and storms; the geologic materials and structure of areas; and observations of past and present erosion and deposition.

## SEA WATER MOVEMENTS

Several different types of water movement produce erosion and deposition along shores and coastlines. Waves, undertow, alongshore currents, tides, and tidal currents interact to bring about the observed results. Of these agents, however, by far the most important are waves and alongshore currents

***Waves.*** Every exposed body of standing water is disturbed to a greater or lesser extent by waves. The size and energy of waves are conditioned by the surface area of the water, by the depths of water, and by the disturbance which creates the waves. Some shores are little affected by wave work because of shoal waters which margin them; others are little affected because of protected positions or short fetch of water facing storm directions; and others, because of resistant rock make-up, yield but slowly. A consideration of wave action necessarily distinguishes between wave types. The two major classes of waves acting on shores and coasts are oscillatory waves and translatory waves.

*Oscillatory Waves.* An *oscillatory wave* is one in which each water particle describes an essentially closed orbit about its position of rest; the wave form advances, but the water particles make little or no advance with the wave. The orbit of the individual water particles has a diameter equal to the wave height, i.e., the vertical difference between trough and crest of the wave. This orbital motion is illustrated by some floating object, such as a cork. The cork may be seen to be at the bottom of its orbit in the trough of the wave rising to the top at the crest of the next wave and again coming to the bottom of its orbit in the next trough. The period of the wave is the time required for a complete orbit of a water particle; it thus coincides with the time interval required for the advancement of the crest one wave length. The orbits, however, are seldom exactly

closed; the water particles ordinarily do not return exactly to the initial position, but describe a spiral course urged forward somewhat by the wind.

Oscillatory waves diminish rapidly with depth (Fig. 20-4). An approximate statement is that at a wave depth equal to one ninth of the wave length, the diameter of an orbit (wave height) is diminished by one half. This rate holds true for each additional ninth of wave length below the surface, and the orbits diminish, therefore,

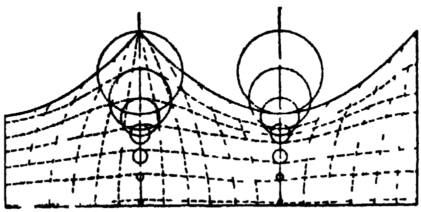


FIG. 20-4. Oscillatory waves. (After Gaillard)

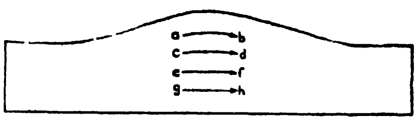




FIG 20-5. Translatory waves.

in geometrical progression. That a submarine ducks under violent wave action by relatively shallow submergence illustrates the point. At a depth equal to one wave length, the orbits are less than one five hundredth (1/534.5) those of the surface.[1] The importance of this progression is obvious when considering the depths to which wave action is effective, i.e., the determination of wave base. ***Wave base*** is defined as the depth at which the greatest surface waves are so diminished as to be unable to move the smallest solid particle resting on the bottom; it is therefore a function of the height and length of the largest waves disturbing a given body of water and of the size of the smallest particles resting on the bottom.

When waves of oscillation approach the shore or progress into shallower water, wave height is generally increased because the wave motion is being transmitted from a larger to a smaller quantity of water. The wave length is decreased, and the form of the wave may become asymmetrical. It breaks if the water becomes sufficiently shoal. This depth is expressed approximately by the rule that waves break

[1] Gaillard, D. D., *Wave Action*, 1935, p. 13.

when the wave height (crest to trough) is equal to the mean water depth. Contributing factors to depth of waves breaking are the configuration of the bottom, strength of undertow, and velocity of the wind.

The size and velocity of oscillatory waves vary in deep water, oscillatory waves exceptionally reaching a height of more than 50 feet; breaking in shallow water, they may achieve a height of some 25 feet. The maximum wave lengths are probably between 2000 and 3000 feet; the greatest length on record, estimated, is 2750 feet[7]. The velocity of propagation, in deep water, is exceptionally as high as 50 miles per hour. Velocity diminishes with decreasing wave length. The waves of shoal waters, therefore, do not travel as fast as the longer waves of deep water zones. In deep water, the velocity is expressed approximately as:

$$V = \frac{L}{T} = \sqrt{\frac{g}{2\pi} L} = g \frac{T}{2\pi}$$

where $V$ is the velocity, $g$ the acceleration of gravity, $L$ the wave length, and $T$ the wave period. Substituting for $g$, the expression becomes.

$$v = 2.27\sqrt{L}$$

where $v$ is the velocity in feet per second and $L$ is the wave length in feet. This simple relation does not hold, however, in shallow water.

An oscillatory wave has both kinetic and potential energy. The former is due to the orbital motion of its particles, and the latter is due to the lifting of water above its mean position at rest. The total energy for deep water waves of trochoidal form is given by the expression $E = wh^2 L/8$ where E is the total energy, both kinetic and potential, $L$ is the wave length in feet, and $h$ is wave height in feet and $w$ is weight per unit volume of the water.[8] The potential and

[7] Johnson, Douglas, *Shorelines and Shoreline Processes*, Wiley, New York, 1919, p. 28.
[8] Krumbein, W. C., *Beach Engineering* in Berkey Vol. G.S.A. 1950, p. 199.

kinetic energies are equal and the former is transmitted forward with the wave. In shallow water the total energy of a wave is somewhat less than for a wave of the same dimensions in deep water: often the difference is on the order of 2 per cent. From the foregoing it can be seen that the calculation of wave energy in foot-tons per linear foot of wave crest can readily be made if wave data are obtained. For example, the formula gives approximately 38 foot-tons per linear foot of crest length for a wave of 100 feet wave length with a 10-foot wave height. Calculations of this type are approximations, for actual waves are seldom geometrically perfect. It is commonly assumed that, for deep water waves, the energy is proportional to the square of wave height. Just outside the breaker line, it is taken as proportional to the cube of the wave height.[4]

In shallow water, the orbits described by water particles of oscillatory waves become increasingly elliptical with depth so that on a bottom affected by this type of wave a water particle travels back and forth in a straight line—forward with the crest, back with the trough. Particles small enough to be moved experience similar back and forth movement, although as explained by Fenneman,[5] the net backwards movement of the particle is probably greater than the forward movement. The finest particles are worked ultimately into deep water where they are undisturbed by wave action. Experimental work on the nature of transport by oscillatory waves, however, is needed. Symmetrical ripple-mark formed by oscillatory waves is found preserved in consolidated sediments as well as in present-day deposits of lake and sea. Several recorded observations show that oscillation sand ripples remained constant in position while deposits of 2 feet or more accumulated. Because the crests of oscillation ripples are sharper than the troughs, this form of ripple-mark is useful in determining the tops and bottoms of deformed sediments; hence this minor structure is useful in working out larger structures in the field.

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[4] Munk, W. H., and Traylor, M. A., "Refraction of Ocean Waves," *Jour. Geol.*, Vol. 55, 1947, p. 24.

[5] Fenneman, Nevin, "Profile of Equilibrium of the Subaqueous Shore Terrace," *Jour. Geol.*, Vol. 10, 1902, pp. 5-13.

*Translatory Waves.* A *translatory wave* is one in which the water particles experience a forward movement with the wave and do not return to the original position. The forward movement consists of a series of semi-elliptical paths traversed by the individual particles. The movement is not confined to the surface but all the water particles throughout the depth partake in it. The semi-ellipses become flattened with depth, and at the bottom the motion is essentially a straight-line displacement (Fig. 20-5). Although the translation of the individual water particles themselves may be short, the impulse is transmitted, and the wave form often travels considerable distance It may be noted in Fig. 20-5 that the wave crest rises above the general level of the water but that there is no corresponding trough depressed below the general water level. Thus the water area between the wave crests is broader and flatter in aspect than the trough between waves of oscillation.

Waves of translation are characteristic of coastal areas. The changes of oscillatory waves, as they advance from deep to shoal water, have been noted; the wave height increases, the wave length and velocity decrease, the front side of the wave becomes progressively steeper than the back slope, and the circular orbits of the water particles become increasingly elliptical. When the wave breaks, some two thirds to three quarters of the wave height is above the still-water level. In breaking, the top of the wave is poured onto the forward slope with a velocity greater than that of wave propagation From the break-line forward the wave is largely one of translation. The mechanics of transformation from oscillatory to translatory waves is not fully understood. In part, the change may be due to the displacements caused by the water poured forward at the break. In large measure, the waves that reach the shores or shoal-water structures are translatory waves.

In the deep sea, waves of translation are not commonly present unless generated by volcanic explosions or by earthquakes. Some of these deep sea waves travel with tremendous velocities; records of velocities as high as 900 miles per hour may be found.[6]

[6] Johnson, Douglas, *op. cit.*, p. 40.

Where an oscillatory wave meets a vertical obstruction, for example a cliff or wall, its crest rises approximately to twice normal height, and the wave is reflected. Thus a large part of the wave energy is exerted against the obstruction as hydrostatic pressure rather than as dynamic stress. Where a wave of translation meets an obstruction, however, the full energy of the wave is delivered as a dynamic impact comparable to the impact delivered by a stream of water under pressure as from a hose or by a stream current. The force of wave action against coasts and coastal structures has been measured by means of wave dynamometers. Readings of over 6000 pounds per square foot have been made. Stevenson found by dynamometer measurements that the average impact of summer waves on an island off the Scottish coast was 611 pounds per square foot; the average winter impact at the same place was 2086 pounds per square foot.

A few examples of unusually severe wave action will help to make the powerful hydraulic action of these waves more graphic. At Wick, Scotland, in 1872, a monolithic block of concrete, 45 by 26 by 11 feet, weighing 800 tons, and bolted to stone blocks beneath by iron rods, was torn loose bodily from a pier, gradually skewed around by successive waves, and finally dropped intact in the lee of the pier. The weight of the monolith and stone, moved in one piece, was estimated to be 1350 tons. Gaillard[7] calculated the necessary pressures to move this mass to be 2015 pounds per square foot. Five years later, the waves outdid themselves at this same place by removing the replacement, a monolithic concrete mass weighing 2600 tons. This is perhaps the most noteworthy example of wave action on record, but many hundreds of other impressive examples have been described. Typical of these is the account of a 12-foot vertical displacement of a concrete block weighing 20 tons at Ymuiden, at the entrance of the Amsterdam Canal; the block was landed on the top of a pier 4 feet and 10 inches above mean high water.

The erosive power of waves is enhanced by the rock fragments carried. In storms, large particles often are cast violently against

[7] *Ibid.*, p. 162

obstructions; the finer particles serve as agents of abrasion. In no small measure are the erosive works of waves due to the effective tools they use. The erosive power of waves, however, is diminished by wave reflection and interference. The turmoil caused by the conflict between advancing and reflected waves is a sight familiar to all who have visited steep shores. Locally the energy of an oncoming wave is directed upward, and a considerable mass of water, although but a small part of the wave itself, shoots upward to surprising height and with great force. At Tillamook Rock, Oregon, the light house stands 132 feet above high water. During a storm, thirteen panes of glass in the lantern were broken, and one rock fragment weighing 135 pounds, was hurled upward and fell back through the roof of the keeper's dwelling practically wrecking it. The dwelling was 84 feet above high water. At Buffalo, New York, a timber-crib breakwater constructed of 12 by 12 inch timbers, 12 feet long, 10 feet between supports, and spaced 5 feet from center to center, was broken. "The waves, dashing against the *vertical walls* of the structure, rose to a great height above it, variously estimated at from 75 to 125 feet, enveloping the breakwater in an immense sheet of water which in falling struck the top of the superstructure with such force as to crush in the same, the large timbers of which it was constructed being broken like pipestems." [8] Gaillard calculates, assuming the unit stress of the timber was 6000 pounds per square inch and that the falling water corresponded to a uniform load suddenly applied, that the breaking load corresponded to a mean pressure of about 1145 pounds per square foot over the entire area of 50 square feet supported by each timber. Overhanging projections of cliff or structure, as well as the tops of caves or crannies against which these vertical currents (hydraulic jets) are directed, are eroded.

It must not be supposed, however, that destructive waves, like those involved in the examples cited, are pure translatory waves Although the static effects of oscillatory waves do little damage to sound structures, the transmutation into translatory movements which takes place on friction exerting surfaces, plus the dynamic

[8] *Ibid.*, p. 106.

impact of water particles with relatively high orbital velocities probably account for damage. The transmutation of oscillatory wave into translatory wave, in part, may take place before the wave breaks; probably most waves which impinge on shallow water structures are compound waves. Much remains to be discovered in the field of wave investigation.[9]

FIG. 20-6 A. Wave refraction, coast north of Oceanside, California. (Courtesy of W. H. Munk and the *Journal of Geology*)

FIG. 20-6 B. Wave refraction around Point Loma, San Diego, California. (Courtesy of W. H. Munk and the *Journal of Geology*)

***Localization of Wave Effects.*** Wave work on shores is not everywhere of the same intensity. At places, glacial striae only a fraction of an inch deep pass beneath the water; wave erosion since the glacial period has not erased them. At adjacent places may be wave-cut cliffs and caves of post-glacial date. The principal directives for wave work are the shape of the shoreline, the topography of the bottom adjacent to the shoreline, exposure, and the composition and structure of the shore.

*Configuration of the Shore.* The configuration of the shore and adjacent bottom determines to a large extent the effectiveness of wave work. It can be noted at almost any time on almost any shore that the waves roll in normal to the shoreline. The waves are refracted as they approach the shore into a position of subparallelism with it,

[9] The Beach Erosion Board of the U. S. Army Engineer Corps and the Scripp's Oceanographic Institution are doing notable research in this field.

for the velocity of the wave is checked progressively along its front as first one part and then another encounters shoal water. Thus the wave swings into a position roughly paralleling the shore. This

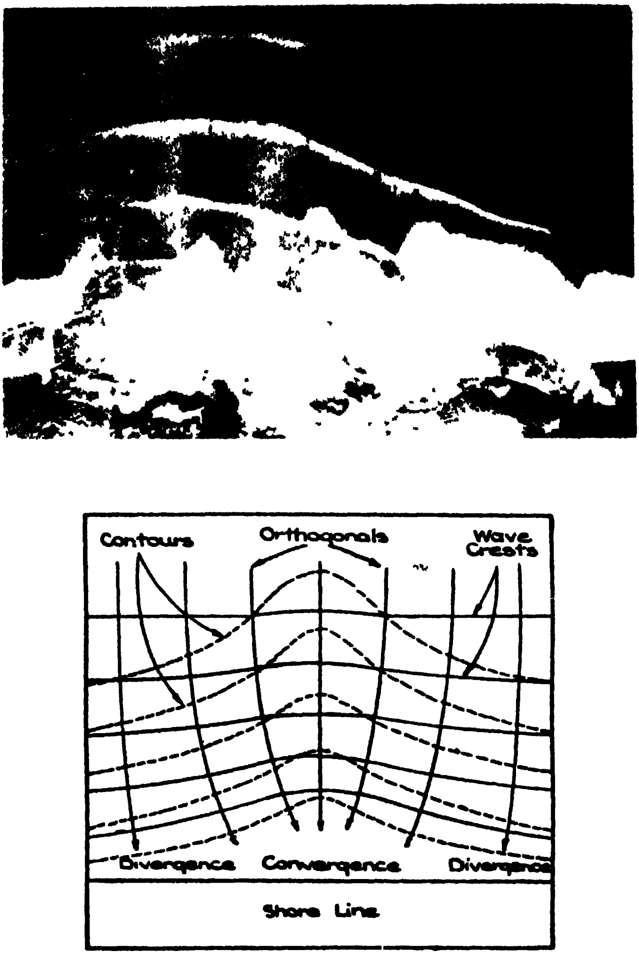



FIG. 20-7. Effect of submarine ridge on waves. (Courtesy of W. H. Munk and the *Journal of Geology*)

is shown in Fig. 20-6A, and Fig. 20-6B. The *orthogonals* are normals to the wave crest. The effect of a coastal projection upon advancing waves

is shown in Fig. 20-7. Convergence of the orthogonals indicates concentration and intensification of wave action; divergence indicates spread and lessening of wave action. These diagrams well explain the concentration of wave attack on headlands, and the relative protection offered by bays, even though not enclosed.

The configuration or submarine topography off-shore has also an important influence on the effectiveness of coastal wave action. The wider the shoal area over which waves must pass in reaching the shore, the less effective they are as erosive agents when they reach it. Irregularities in relief of the adjacent submarine topography locally concentrate or diffuse wave action on the adjacent shore and thus must be taken into account in shore studies. This is clearly shown in Fig. 20-7, which shows the convergence of orthogonals caused by a submarine ridge.

*Exposure.* Exposure of the shore with reference to the prevailing winds must also be taken into account when planning shore structures. More important, however, is the exposure with reference to the maximum storm winds, which may blow from quite a different quarter than the prevailing winds. The *fetch* of the wind, or distance it blows over open water, is critical, for damaging storm waves are not brewed in a teapot. Taking due account of the fact that storm-making winds vary considerably in intensity and direction during their course and at different extremities of their reach, the empirical formulae of Thomas Stevenson give surprisingly good approximations for expected wave heights as shown by observational checks. Stevenson observed that the heights of waves are proportional to the square root of their distances from the windward shore, if the depth of water is sufficient to permit development.[10] This is stated as:

$$h = c\sqrt{f}$$

where $h$ is wave height in feet, $f$ is fetch in nautical miles, and $c$ is a coefficient varying with wind velocity, which for strong gales, with deep enough water along the fetch to permit full wave development,

[10] Gaillard, D. D., *op. cit.*, p. 50

is taken as equal to 1.5. For short reaches and violent squalls, Steven son considered that:

$$h = 1.5\sqrt{f} + (2.5 - \sqrt[4]{f})$$

where $h$ and $f$ are height and fetch, respectively, gave better results. Table 20.1 gives a comparison between observed wave heights and the heights as calculated from the formulae of Stevenson. In this table the second formula was used for the calculation of the first eight observations, and the first formula for the last five observations

TABLE 20.1.* COMPARISON OF OBSERVED WAVE HEIGHTS WITH HEIGHTS COMPUTED FROM FETCH

| Locality: Lake Superior and San Pedro Bay, Cal. | Fetch (nautical miles) | Height of Wave | |
|---|---|---|---|
| | | Observed (feet) | Computed (feet) |
| Duluth Basin | 0.375 | 1.5 | 2.6 |
| Duluth Basin | .428 | 1.7 | 2.7 |
| Duluth Basin | .641 | 2.0 | 2.8 |
| St. Louis Bay | .916 | 2.0 | 2.9 |
| Duluth Basin | .428 | 2.3 | 2.7 |
| Portage Lake | 1.086 | 3.0 | 3.1 |
| Duluth Basin | .718 | 3.8 | 2.9 |
| St. Louis Bay | 1.923 | 4.5 | 3.1 |
| San Pedro Bay, Cal. | 15.64 | 6.0-7.0 | 5.9 |
| Stannard Rock | 41.45 | 11.9 | 9.7 |
| Marquette, Mich. | 116.63 | 15.3 | 16.2 |
| Portage Breakwater | 82.50 | 16.5 | 13.6 |
| Duluth Canal | 258.62 | 23.0 | 24.1 |

* From Gaillard, D. D., *op. cit.*, p. 52

*Composition and Structure.* The composition and structure of the materials of the shore and coast are highly significant in the development of the shore features and types of shoreline. With equal exposure to wave attack, weaker zones are etched out and the more resistant zones gain relative prominence and relief. Dikes or other minor intrusions, shattered or sheared zones, beds of varying resistance in a sedimentary or metamorphic sequence, and deeply weathered portions are causes of differential resistances to wave attack which are sought out with unfailing percipience by the waves. The structure, or attitude, of these differentially resistant zones directs the course of wave erosion and in large measure determines the character of the shoreline. Drainage of the area in back of the coastline and the presence or absence of shore ice are to be considered likewise.

***Currents.*** Waves are not the only water movements that modify shore zones. The variety of currents that stir the waters of the seas is surprising. Density currents, salinity currents, river currents, tidal currents, wave currents, undertow, convectional currents, and perhaps others affect greater or lesser volumes of water, and to some extent, at least locally, modify in one way or another the adjacent lands. Relatively few of these, however, greatly affect the configuration of the shore zones, and these few are of unequal importance. Of particular engineering significance may be mentioned: undertow and rip currents which act in a direction more or less normal to the shore, tidal currents which are locally effective, and alongshore currents which are the most significant of all at most places.

*Undertow.* Where oscillatory waves break or translatory waves advance on a shore, excess water is pushed landward; in other words, an hydraulic head is created, and the surplus water must find escape. If this escape is along the bottom, a broad outflowing current is formed called an *undertow.* On shallow shores, the water returning seaward is generally met by the advancing waves inside the line of breakers and thrown shoreward again. In this situation, an escape current may be generated that flows parallel to the shore until depressions are discovered that give a seaward exit. Where the beach is moderately steep, the undertow may have velocity enough to move

out fine particles of the shore material. The onrush of a breaking wave may carry both fine and coarse material landward; but the returning water from it, with lesser velocity and lesser transporting competency moves seaward only the fine sediment. An old generalization states that sand cannot live on a gravel beach. The extent to which this is true depends very largely upon the principle just pointed out. Concentrations of undertow, probably due to configuration of the bottom, give rise to local variations of strength. At some places the undertow is a powerful current, locally called a rip current. The velocity of the undertow is checked as it reaches deeper water, and as its cross-sectional area increases. If the bottom slope suddenly steepens, as it does off many shorelines, the undertow deposits a large fraction of its load at that place.

*Tides and Tidal Currents.* The rise and fall of the tide itself on an open coast are relatively ineffective in transforming the shoreline. On tidal shores, however, there is always the possibility of a conjunction of storm and wave intensity with the maximum tides. When this happens exceptional wave damage is often the result.

On irregular shores, the rise and fall of the tide may be transformed into tidal currents which locally may have velocities up to some 10 or 12 miles per hour. These, called by some *tide rips*, are active agents of erosion or deposition. A funnel-shaped re-entrant in the shoreline concentrates tidal effects, as shown by the 50-foot tides and many tidal currents of the Bay of Fundy region. In contrast, a bottle-like re-entrant with a restricted tidal entrance minimizes tidal effects, as shown by the general absence of tidal phenomena in the Mediterranean Sea. An interesting example of the effect of irregularity of shoreline is shown at St. John Harbor, New Brunswick. There the tide rises and falls more rapidly than water can pass through the narrow inlet so that differences of head, of maximum difference of 10 feet, are created alternately inside and outside the inlet. Hydraulic currents result, and a "reversible waterfall" is produced by the rise and fall of the tide.

Depending on the topography and configuration of the coast, tidal currents may be effective to depths as great as a thousand feet

or more. According to Harris[11] currents of 0.4 nautical miles per hour will move fine sand, currents of 1 knot will move fine gravel, and currents of 3.5 knots will move angular pebbles up to an inch and a half in diameter. Many tidal rip currents, therefore, are capable of scour. In the earlier days of settlement, a number of tidal mills were operated along the New England coast; recently a multimillion dollar federal project for harnessing of tidal energy was begun and abandoned at Passamaquoddy Bay, near Eastport, Maine.

***Alongshore Currents.*** Those inshore currents which move more or less parallel to the shoreline are known as *alongshore currents,* or *littoral currents.* Complementary to wave work, they are at many places highly effective agents of transportation and deposition.

Alongshore currents originate in several ways. Where waves impinge obliquely against the land, the alongshore direction of current is the resultant of the oblique advance of the wave up the beach and its return down the steepest slope which is usually normal to the strandline. This is illustrated by observing the migration of small pebbles. An onrushing wave advancing at an angle to the shore picks up a pebble and moves it diagonally up the beach. The return water rolls it down-slope where it is met by the next wave to be moved diagonally up-beach again. The pebble describes a zig-zag path parallel to the shore. The higher the angle of obliquity with which the waves impinge, the more rapid and vigorous the resultant current. With angles of ten or more degrees, currents with velocities of several knots per hour may be formed. Wave refraction fortunately lowers the angle, reducing the velocities and damage that otherwise might result. Littoral currents of this type frequently shift direction. On the east coast of India, for example, they shift seasonally with the monsoonal winds. Studies on the shoreline between Madras and Calcutta showed that more than 1,000,000 tons of sand a year were shifted back and forth annually past a given point. Although the directions are variable, on many shores where these currents are found, one direction of movement predominates.

[11] Harris, R. A., "Manual of Tides," Pt. 5, 1907, p. 123.

Previous mention has been made (page 493) of alongshore currents developed on broad shallow beaches, where the water brought in by waves is prevented by breakers from escaping seaward. The surplus water moves parallel to the coast, seeking an outlet of escape. Gaillard cites the Florida coast as a place where littoral currents of this origin are found. Locally, also, tidal currents are directed into littoral directions and move along parallel to the shores for limited distances.

The engineer is mostly concerned with the zone extending from not far below low water to safely above high water. This is the zone of maximum wave work which loosens and abrades material. This is also the zone of maximum turbulence which stirs up the bottom as waves break. And consequently this is the zone of maximum littoral drift.

## Erosional Features of Shorelines

The erosion forms of the sea margins are principally those cut by waves. The depth and fetch of water, exposures, and rock type and structure, condition and localize wave effects. Littoral and offshore (rip) currents distribute the products of wave erosion, they themselves are minor agents of destruction.

The most common and universally distributed wave cut forms are wave-cut cliffs and the wave-cut benches which margin them. The heights and widths of these complementary forms vary as do the rates of wear which make them. No shore is so protected that minor wave action, at least, does not reach it. The low cliffs of unconsolidated rock contrast with bold hard-rock cliffs facing deep water of long fetch. But the 2-foot shore escarpment of loose earth and the 300-foot sea cliff of solid rock belong to the same genus.

Only locally is the rate of cliff recession in consolidated rock rapid enough to give rise to concern or to necessitate engineering works for its control. One interesting example, however, was the excessive recession of the cliffs at Lime Regis, England. There a horizontal series of interstratified shales and limestone required protection (Fig. 20-8). The soft shale beds were being rapidly eroded,

and the more resistant limestone layers, which were undermined, wasted by rock-falls. The protecting wall shown in the diagram successfully stabilized the cliff.

Minor erosion forms, which nevertheless are locally prominent and of considerable interest, are chasms, sea caves and spouting horns, sea arches, and rock stacks. These features, which are developed only in consolidated rock, are results of wave attack localized by exposure, wave refraction, or by weak zones in the rock. Steep-walled, short *chasms* are cut back at many places on rocky shores along fractures or other relatively weak zones. Local undercutting of a cliff gives rise to a *sea cave;* the upward deflections of waves at the back of a cave erodes the roof. Some caves thus get chimney like openings to the surface through which water may spout at times of favorable tide and wave incidence; these are called *spouting horns.* Inequalities of erosion may cut through a protuberant part of a cliff, forming a sea arch; or a projection may be separated from the cliff, forming a small rock island, called a *rock stack* (Fig. 20-9).

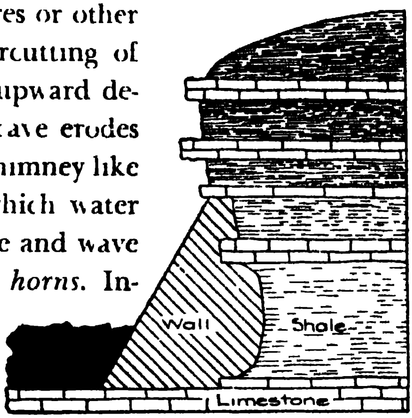



FIG. 20-8 Wave cut bench and cliff Cliff recession checked by protecting wall (After C. S. Fox)

### DEPOSITS

Transportation and deposition of sediments by waves and currents are often of economic interest because of the use made of coastal zones. Water thoroughfares are locally impeded, harbors shoaled, and marine structures silted. Changes in sedimentation often cause migration of shoals and inlets. Further, control of transportation often controls erosion; for, if the wave-produced debris is not removed, shore protection is the result. At many places, shorelines of erosion have been altered to shorelines of deposition by engineering works. Also, many sea or lake deposits are useful sources of construction material. At some places, recession of lake or sea has

left useful deposits high, dry, and accessible; at other places, storm waves have tossed up deposits which are accessible most of the time Many deposits of both types have been successfully exploited. For

FIG. 20-9 A. Small rock stack, Bar Harbor, Maine.

FIG. 20-9 B. Percé Rock, Quebec. A large rock stack (Photo by Robert Dow)

these reasons, therefore, transportation and deposition by waves and currents are of interest to engineers.

The generalization that debris carried by a fluid agent tends to be deposited wherever velocity is checked is as true for marine and lake sedimentation as it is for that of streams or wind. Of the depos-

its built by waves and currents, beaches, barrier beaches, spits, hooks, tombolos, bars, and wave-built terraces are among the more commonly encountered types.

***Beaches.*** Beach deposits are familiar to all. Technically, the *beach* (or shore) is the zone extending from low water to the upper limit of high water. At many places, *beach ridges* which rise above the average high-water wave limit are found on the upper part of the shore. These formations result from both wave and current

FIG. 20-10. Beach ridge with small lagoon.

transportation. Debris from the erosion of headlands or other exposed portions of the shore is drifted alongshore by littoral currents. In the more sheltered places, as at the heads of re-entrants, or where littoral currents cannot carry the material away, the coarse fraction of the load is driven landward and heaped up into ridge form by the waves. The fine fraction tends to be worked seaward by backwash, undertow, or rip current. Thousands of indentations in the coastline have beaches built of materials eroded from the enclosing headlands or from adjacent shores. They are often of crescentic form and are called *crescent beaches* or *pocket beaches.*

Many beach ridges are barriers to drainage; behind them, brackish or fresh water lagoons or marshes have formed (Fig. 20-10).

The material composing a beach varies with the strength of wave action, the distance the material has traveled, and with the character of the rock fragments; thus sand, gravel, cobble, or even shell beaches are found at various places. If the material of a beach consists dominantly of flattened pebbles, it is often called a *shingle* beach. Elevation of the land or lowering of the water level has left many beach ridges far inland from existing shorelines. Because the material composing them is often valuable for construction, recognition of these generally level-crested ridges as beaches is occasionally of service in the search for construction materials. Many examples of use of elevated beach ridges in the Great Lakes region as well as other formerly expanded lake areas and along the coastal regions could be given. The beaches of present-day shorelines comprised of coarse sand and gravel are often good sources of construction material and have been much used for this purpose. Beach sand or gravel is usually clean, moderately to excellently graded, and the weaker rock types have generally been eliminated by vigorous wave action. Many beach gravels are so coarse as to require crushing.

*Barrier beaches*, or *offshore beaches*, are elongate deposits parallel to the shoreline and separated from it by a lagoon of salt or brackish water. They are built by material drifted along by littoral currents or washed in across broad, gently shelving bottoms by waves Barrier beaches are notably developed along many miles of the Gulf of Mexico coast, and they enclose the lagoons which make the so-called inside water route down the east coast from New Jersey to Florida. Fig. 20-11 * illustrates this form.

Alongshore currents build many deposits where the velocity of the current is checked by deeper water. A sudden curvature of the shore which the current is not able to parallel directs the current into water of increasing depth and consequently to deposit. If one end of the deposit is attached to the mainland, it is termed a *spit*

* Fig. 20-11 and all subsequent figure references marked with a black star refer to colored maps to be found between pp. 568 and 569.

(Fig. 20-12). If wave action curves the end of the spit, it is called a *hooked spit* or *hook*. Sandy Hook, off New York, is a well-known example of this class. Many harbors have been formed by spits and hooks. Familiar examples are Provincetown, Massachusetts, Galveston, Texas, and the harbor for Erie, Pennsylvania, which is shown in Fig. 20-13.* In the lee of islands, spits are often built, if these connect the island to the mainland or tie two islands together, the deposit is called a *tombolo* (Fig. 20-14). The extension of a spit across the mouth of a bay may more or less completely block off the inlet. These

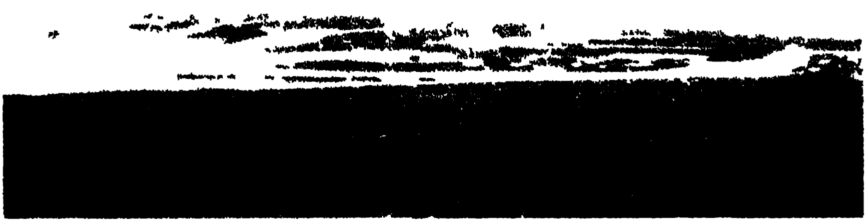
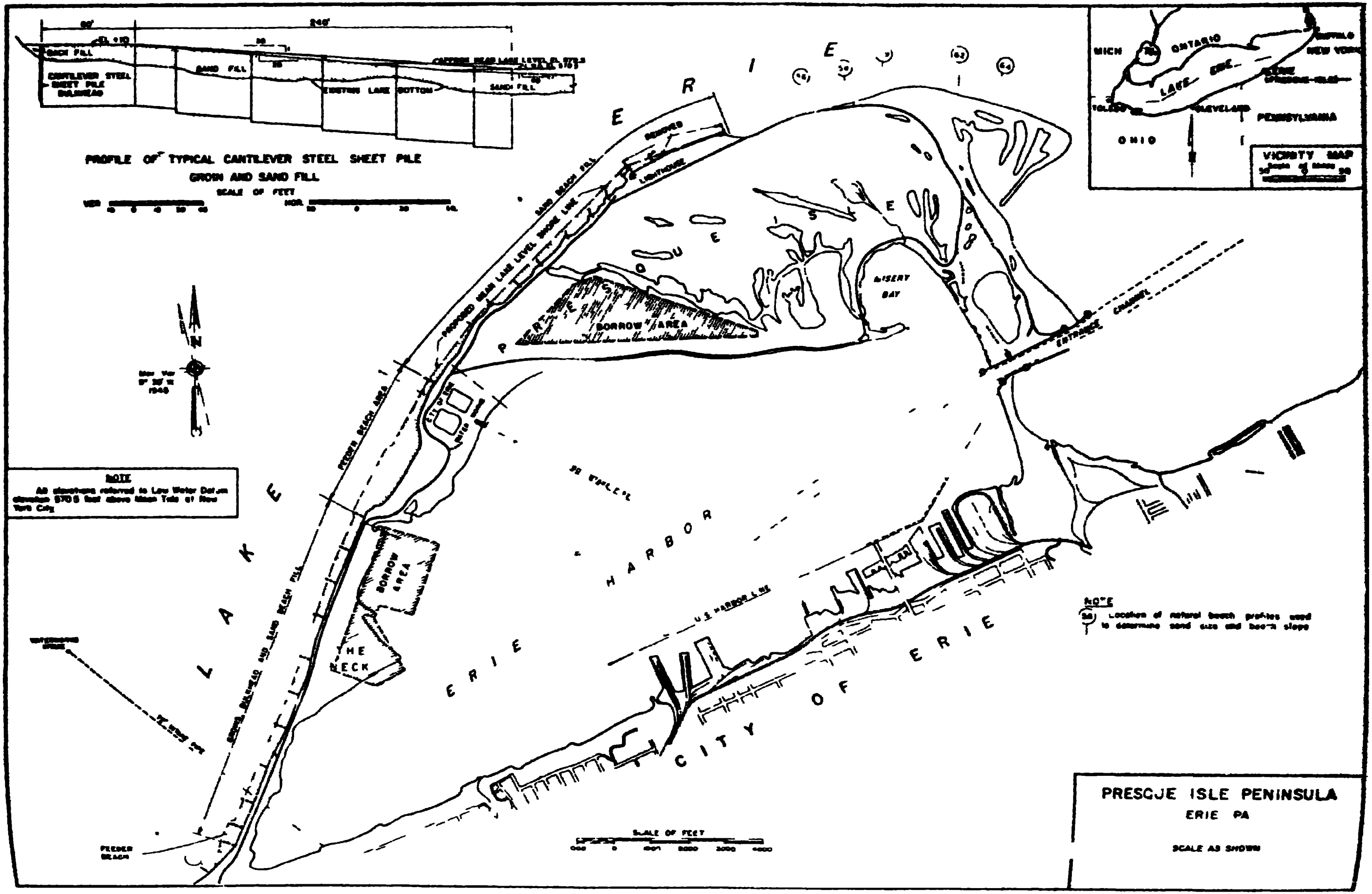


FIG 20-12. Hooked spits (Photo by F. H Perkins)

baymouth deposits are called *bars*. It was pointed out in the discussion of wave erosion that coarse material tends to be worked landward and fine material to be worked seaward, certainly by rip currents and probably by undertow. As this fine material reaches deeper water, often at the margin of the wave-cut bench, deposits called *wave-built terraces* are made. The position of the wave-built terrace was shown in Fig. 20-2.

An interesting application of the principles just discussed is shown by the works to protect and restore the shore of Presque Isle Peninsula (Fig. 20-13*, 13A), a hooked spit forming the protection to the harbor of Erie, Pennsylvania. The neck at the base of the spit was breached three times between 1833 and 1917. Rubble walls, riprap, and bulkheads have been built and partially destroyed throughout the history of the harbor. Investigation shows that about 18,000 cubic yards of sand are supplied annually to the root of the peninsula


PROFILE OF TYPICAL CANTILEVER STEEL SHEET PILE
GROIN AND SAND FILL
SCALE OF FEET
BACK FILL
CANTILEVER STEEL SHEET PILE BULKHEAD
SAND FILL
EXISTING LAKE BOTTOM
SAND FILL
LAKE ERIE
PRESQUE ISLE
MISERY BAY
BORROW AREA
LIGHTHOUSE
ENTRANCE CHANNEL
PROPOSED MEAN LAKE LEVEL SHORE LINE
SAND BEACH FILL
FEEDER BEACH AREA
GROIN, BULKHEAD AND SAND BEACH FILL
BORROW AREA
THE NECK
ERIE HARBOR
U.S. HARBOR LINE
CITY OF ERIE
FEEDER BEACH
NOTE
All elevations referred to Low Water Datum elevation 570.5 feet above Mean Tide at New York City
NOTE
Locations of natural beach profiles used to determine sand size and beach slope
VICINITY MAP
MICH
ONTARIO
LAKE ERIE
BUFFALO
NEW YORK
TOLEDO
CLEVELAND
PENNSYLVANIA
OHIO
SCALE OF FEET
PRESCJE ISLE PENINSULA
ERIE PA
SCALE AS SHOWN

from the west in a zone extending lakeward to the 3-fathom line. Along the groynes in the southwest, 19,000 cubic yards are lost annually; and from a stretch of 31,000 feet east of the groynes, the annual sand loss is 285,000 cubic yards. Wave refraction studies show that easterly storms do less damage than westerly storms. To protect the highway and beaches and to preserve the peninsula as a breakwater for the harbor the following proposals have been made: (1) to protect the neck by a heavy bulkhead. For the most part this is already built; (2) to restore the beaches by artificial fills and construct groynes. It is planned to place a beach some 300 feet wide along the neck about midway between the groynes and the Water Works Jetty. This will require about 1,500,000 cubic yards of sand, which can be pumped from the east end or drawn by sand suckers. Supplementing this a stockpile of some 1,000,000 cubic yards of sand will be placed as a feeder beach near the waterworks to supply sand for littoral current nourishment to beaches to the east.[12]

[12] Olmstead, L. W., and Lynde, G. A., *Civil Eng*, Vol 28, 1958, p. 42.

## Types of Shorelines

Various classifications of shoreline types have been proposed. An easily applied classification is one based on relative changes of sea level within recent geologic time.[13] This gives a fourfold division of shorelines as follows: shorelines of submergence, shorelines of emergence, compound shorelines, and neutral shorelines.

***Shorelines of Submergence.*** In many parts of the world the water levels have risen with respect to the lands, or the lands have sunk relative to water levels. Consequently, many miles of coastline are drowned or submerged.

The features of a drowned coast depend in large measure upon the topography before drowning. The submergence of a flat area results in a relatively straight coast, with broad, shallow-water flats margining the shore. The river valleys become tidal estuaries, which, although maintaining riverine outline, are abnormally broad and shallow. The Chesapeake Bay region shows the characteristic irregu-

[13] Johnson, Douglas, *op. cit.*

larities of a drowned river system, and, although the area has experienced both positive and negative movements with respect to sea level, it illustrates fairly well the effects of submergence of an area of low relief.

FIG. 20 14. Tombolo, Point of Maine, Maine.

The submergence of a hilly area results in an extremely irregular coastline. Ridges and hills become peninsulas or islands, and the valleys and lowlands become estuaries and bays. As a result, the coastline is enormously lengthened. The straight-line distance from Portland, Maine, to Eastport, Maine, is about 200 miles; because of submergence, the coastline distance is conservatively estimated at 2000 miles. Many rocky islands and peninsulas, bays and estuaries reaching far inland, and irregular depths of offshore water are marks of submergence. Examples of submerged areas of hilly topography are the New England and Maritime Province coasts. The most scenic coastlines of the world, the glacially sculptured mountainous coastlines of Norway, Chili, and Western Canada and Alaska, are other examples of drowned coasts.

***Shorelines of Emergence.*** Because adjacent to the lands, sea floors are graded by waves and currents, emergence or uplift of these bottoms tends to give relatively straight shorelines. Few islands, few

bays or harbors, and gradually increasing depths of water offshore are marks of emergence. It has been previously noted that barrier beaches are characteristic of areas where water depth increases gradually offshore. Therefore, while not restricted to shorelines of emergence, the barrier beach is very often present off relatively flat emergent areas. In addition, elevated shore features, raised beaches, abandoned sea cliffs, and others are often recognizable relics of former water levels which demonstrate emergence. The coast of Florida illustrates the relative uplift of a lowland area, and the coastline of California illustrates the emergence of a relatively rough area.

***Compound Shorelines.*** Many, if not all, shorelines have had a complex history of up and down movements relative to sea level. A shoreline which records both positive and negative movements is called a compound shoreline. Usually, however, the effects of either submergence or emergence are dominant, and shorelines are most conveniently named according to the dominant characteristics displayed. The coast of New England, for example, has shifted both up and down. Elevated marine deltas and beaches locally record a higher stand of the sea; but the irregular coastal outline, drowned rivers, and associated features are so prominent that it is generally cited as a type example of submerged coastline. Nevertheless, in that region, recognition of emerged shore features has successfully guided the search for gravel deposits to the elevations at which marine deposits have been left above the present sea level. Of even greater significance to the engineers of the region is the delimitation of the areas in which troublesome marine clays may be expected.

***Neutral Shorelines.*** Neutral shorelines are defined as those that owe their principal characteristics neither to submergence nor to emergence. In this class, therefore, are included those built by delta advance, organic growth (as coral reefs), or by volcanic flows or pyroclastics.

## Control of Wave and Current Action

Engineering measures for regulation of wave and current action are of two classes. One of these includes those measures designed to

improve or protect shore and coastal property; the other includes those measures designed primarily to create, improve, or maintain water trafficways and facilities. It is beyond the scope of this book to detail the various structures used for these two types of project. Consequently, only a brief summary of some of the structures that have been used in this branch of engineering is included.

***Coast and Shore Protection.*** The principal structures used are sea walls, bulkheads, and revetments which are built parallel to the coastline for protection of the area immediately in their rear; groynes and jetties which are built at high angles to the coastline for the protection or improvement of the beach and coastline; and offshore breakwaters which are built at various angles to reduce wave action onshore.

*Sea Walls and Bulkheads.* Sea walls are massive structures designed to protect the areas immediately in their rear from damaging wave action. Because they are designed to prevent storm damage they are necessarily massive and correspondingly expensive. They are particularly subject to toe erosion. To minimize wave damage, sea walls should be set back as far as possible above high water, and sharp deflections in direction should be avoided where possible since sharp angles and re-entrants concentrate wave attack. Vertical faces are often used, but sloping faces which act as expending walls are more stable, and at several places parabolic faces as shown in Fig. 20-15 have been used to dampen wave action. Many sea walls serve also as retaining walls for natural earth or fill behind them; consequently the same provision for resistance to earth pressures and for drainage of impounded earth must be made.

*Bulkheads* serve the same purpose as sea walls but are of lighter construction, and hence more economical. They are usually made of sheet steel piling or heavy timber. They are suitable where wave action is less intense, or where a system of complementary groynes has been installed.

*Revetments,* like sea walls and bulkheads, are designed to protect the land immediately behind them. Most revetments are made of stone laid up as a protecting face against low earth cliffs at the shore-

*Courtesy Norman Wood*

FIG. 20.15 Sea wall with parabolic face Northport, Maine.

line The stone blocks should be large enough to resist dislodgment by any expected wave impact They should be high enough to prevent overtopping by any but the greatest storm waves, and should be properly chinked to prevent earth being washed through them from the rear.

Sea walls, bulkheads, and revetments give no protection to the beach in front of them. At many places, indeed, where not complemented by other measures, they have promoted beach scour by limiting the advance of waves and increasing the backwash. Further, the beach is robbed of the protective cover of new material added by coastal erosion, the abrasion and removal of which absorbed some wave energy. Good design in founding sea walls and bulkheads, therefore, allows an ample depth safety factor against toe erosion. The more gently sloped a revetment is laid, the better, as it becomes an expending wall which dissipates wave energy. Many miles of bulkhead and revetment are damaged each year, and maintenance

costs in labor are high. Many cottage holders are resigned to annual revetment or bulkhead repair. Used in combination with groynes or jetties, however, sea walls, bulkheads, and revetments are commonly satisfactory and economically maintained.

*Groynes and Jetties.* A groyne is a wall built essentially at right angles to the general trend of the coastline. Its function is to check littoral drift and, consequently, to cause deposition. Groynes of sheet steel, concrete blocks, stone, and creosoted wood are used. They are built on the beach and need not be extended above high tide nor below low water to be effective. The horizontal spacing of groynes depends upon the amount of material moved along the beach; the greater the amount moved, the wider is the permissible spacing of groynes. The ratios of length of groyne to distance to the next groyne are usually between 1.1 and 1:3 Correct spacing also takes into account the direction from which the most damaging storms customarily approach Brown[14] suggests that after the length of groyne has been determined, a line in the direction of maximum storm approach through the end of the groyne to the bulkhead or sea wall (coastline) helps to choose the horizontal spacing within the limits of the 1:1 and 1:3 ratios, which he considers to be the ordinary range of effective spacing.

Unless joined to a sea wall or bulkhead, the landward end should be protected against flanking by storm action (Fig. 20-16). Groynes must permit some material to pass to leeward if the littoral drift is uniformly or dominantly in one direction, because, if the area adjacent is "starved," erosion or scour is probable. Many designs have been developed, including permeable groynes. The effectiveness of permeable groynes has been clearly demonstrated. In the presence of littoral drift, groynes change the shore from one of erosion to one of deposition, a change which not only enhances the beach but also protects the coastline from erosion. The leeward groynes should be constructed first. The disadvantage of groyne systems is that they interfere somewhat with free use of the shore, and that they are con-

[14] Brown, E. I., "Beach Erosion Studies," *Trans. Amer. Soc. Civil Engrs*, Vol 66, 1940, p. 889.

FIG. 20-16. The top view shows the failure of a solid groyne due to erosion at the landward end: the lower two views, taken about a month apart shortly after the construction of permeable groynes, show the restoration of the beach. Near Racine, Wisconsin. (Courtesy of Sydney M. Wood, from the *Illinois Engineer*)

sidered by some to be unsightly A further disadvantage is that the shore to the leeward of groynes may be starved of sand, and therefore subject to erosion.

Many examples of shore control by groyne construction could be

given. One will serve to illustrate their use. At Cudahy Park, Sheridan, Wisconsin, a 50- to 100-foot cliff of unconsolidated material was receding under the combined attack of waves and slope wash at a rate of approximately 2 feet per year. Because the land being lost was valuable, the following measures were taken. Groynes of precast concrete units, 200 feet long, spaced 200 feet apart were installed. The cliff was trimmed back and planted, underdrainage provided, and surface drainage deflected away from the cliff to a safe outlet. The measures have been successful.

Jetties are essentially large massive groynes, which project into deeper water. They are used to protect long open stretches of beach or to protect inlets.

*Replenishment.* Locally on some shores, good artificial beaches have been created and eroded beaches restored by dumping or pumping sand. Where the fill is protected by groynes, or where alongshore currents and undertow are absent, these fills have been moderately successful. If erosion is slow, renewal of the fill may be more economical than construction of retaining measures. However, at most places, fills must be combined with groyne systems, or they are too rapidly lost.

***Traffic Works.*** In addition to the shore works which have been described, those designed to maintain water trafficways may be mentioned briefly. Dredges have long been used and are necessary to the maintenance of many channels. However, if sediments which are deposited in harbors or channels can be forced into deeper water, or the currents which carry them can be deflected, dredging can be reduced. Besides measures for sediment control, construction of sheltering basins or artificial harbors is locally necessary on unindented coasts. Two principal structures are used in these works, the jetty and the breakwater.

*Jetties.* The use of jetties for shore protection has been mentioned. They are also used to protect inlets. Where alongshore currents move into the deeper water of an inlet, deposition commonly takes place which clogs the inlet and often forces its migration. Large jetties aid in the protection of inlets, in part by deflecting the cur-

rents to deeper water, and in part by trapping the sediment outside the channelway. Built at inlets, they also constrict tidal inflow and outflow; thus the scouring capacity of those currents aids in maintaining the channel. Jetties have been successfully used, also, at the mouths of delta distributaries to prolong the seaward current, and to constrict it beyond the immediate mouth of the distributary so that sediment may be swept through and beyond the navigable channel.

*Breakwaters.* Breakwaters are offshore walls designed to trip and impede the landward progress of waves. They are used to create a shipping haven where no well protected natural harbor exists. Many of these structures are successful, and the numbers of "made" harbors is surprising. Sedimentation within the protected area, however, may be excessive, as for example at Santa Barbara, California. Locally, breakwaters have been constructed also as protective measures for shorelines.

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CHAPTER XXI

# THE WORK OF GLACIERS

THE MOST IMPORTANT SOURCES OF CONSTRUCTION MATERIALS in the northern states are deposits made by recent widespread ice sheets. In many of the glaciated states sand and gravel have a higher dollar and cents value than any other geological product taken out of the ground. The civil engineer is directly concerned with the quality, quantity, and location of deposits suitable for concrete aggregate, bituminous mixes, and other purposes. If it is estimated that haulage to a project location costs between five and ten cents a yard-mile, the importance of material location becomes immediately apparent. Material surveys to determine the nearest adequate sources of acceptable materials, consequently, must be made in advance of construction. Blind digging in search for sand and gravel is wasteful and commonly fruitless. Hence the ability to recognize various types of glacial deposit by topographic aspect and associations is often extremely useful to the engineer.

In addition to their use as sources of construction material, glacial deposits are of engineering importance because, in regions that have been ice covered, most engineering construction (probably more than 90 per cent) is founded upon or in them. The highway engineer, foundation engineer, and soils mechanics specialist, therefore, should be familiar with deposits of glaciers. When dealing with foundation problems in glaciated regions, the engineer is more effective in practice and more reliable in judgment and prediction if thoroughly acquainted with glacial deposits—their characteristics, forms, and relationships.

## Types of Glaciers

Wherever more snow accumulates in the winter than melts or evaporates during the rest of the year, glaciers may be built. Even within the tropics at altitudes above 16,000 to 18,000 feet glaciers are found. In more temperate latitudes, glaciers are found on less lofty mountains; in the United States the snowline varies from 6000 to 10,000 or 11,000 feet. In the colder latitudes the snowline is further depressed, and many glaciers terminate in the sea. The two critical factors are thus seen to be low summer temperature, and precipitation in excess of loss. Present-day ice sheets of Greenland and Antarctica cover somewhat more than 5,500,000 square miles of the earth's surface. In former times, extensive ice sheets covered thousands of square miles in the temperate regions of both North America and Europe. The foregoing statements suggest a twofold classification of glacier types: ice sheets, or continental glaciers, and mountain or valley glaciers.

***Ice Sheets.*** *Ice sheets,* or *continental glaciers,* as indicated by the name, are large masses of glacial ice which overspread wide areas. A rigorous climate permits the maintenance of present-day continental glaciers over Greenland and Antarctica. In the recent past continental ice sheets spread over much of the northern portion of both North America and Europe. So recent, geologically speaking, was this ice invasion of now temperate regions, that post-glacial modifications of the ice work are hardly to be recognized; only locally are the results of the last ice advance significantly dissected or altered

***Mountain Glaciers.*** *Mountain* or *valley glaciers,* as the name suggests, are those streams of ice that occupy mountain valleys. At the present time, most of those glaciers are located in mountainous terrain; hence, the synonomous terms *mountain glaciers, alpine glaciers,* and *valley glaciers.* Although today they are somewhat restricted, during the recent glacial epoch mountain glaciers were more abundant and reached to lower elevations in the tropical and temperate latitudes than existing examples. Followed up, valley glaciers lead into either ice sheets or, more commonly, into snow

Fig. 21-1. Mountain Glaciers, Alaska. Note formation of medial moraines where tributary glaciers enter. (Bradford Washburn)

fields. The movement of the ice is down slope at rates which vary from an almost imperceptible advance to as much as 50 feet per day. In Alaska and other regions where mountain glaciers extend to a plain at the foot of the mountains, bulbous enlargements, called *piedmont glaciers,* are abundant. The famous Malaspina Glacier of Alaska is a superb example of piedmont glacier. Fig. 21-1 shows the aspect of mountain glaciers.

### The Work of Ice Sheets

Because glaciers are in motion, they modify both by erosion and by deposition the surfaces over which they advance. Glacial effects, however, should not be too greatly magnified in the mind. Mountain ranges, great plains, and other major topographic features are neither built nor destroyed by glaciation. The topographic detail of a glaciated region is largely glacial, but the major features are preglacial.

***Erosion.*** Glacial ice erodes in two ways. It is able to tear out of place, or *pluck*, partially loosened material around which it has closed. The more highly jointed the rock over which the glacier moves, then, the more vigorous is the plucking action of the ice. Material incorporated in the basal layers of the ice *abrades* or scours the bedrock over which it passes, much as sandpaper abrades a wooden surface. The action of a glacier thus may be likened to that of a giant rasp wearing down the rocks over which it advances. Indeed, so much material may be incorporated in the basal layer that, locally, forward movement is retarded or checked. The overladen portion then may be overriden by ice thrust from behind. Thrust faults and shear zones are commonly observed in active glaciers. By this mechanism, rock debris eroded from the bed is elevated to positions above the glacier base.

During glacial advance, not only is bedrock eroded, but the fragments in transport themselves are also abraded and ground to smaller sizes. The resistant and tough rock types, for example granite, may maintain considerable fragment size for long distances; whereas, pieces of less resistant rock types, such as shale or slate, may lose

identity and be ground to rock flour within comparatively short distances.[*]

Polished and smoothed rock surfaces are found in areas that have been covered by glacial ice. In the course of ice advance, preglacial soils are incorporated in the ice, and weathered surfaces of the ledges are commonly removed to expose fresh rock. Many bedrock hills have but little soil left on them.[*] Glacially smoothed and polished ledges are especially numerous where the bedrock is a fine textured type that has been little affected by post-glacial weathering. Commonly, the smoothed or polished ledges are grooved or scratched. These marks (Fig. 21 2) called *striae*, or *striations*, were caused by the dragging of rock debris across them by the ice; they indicate the direction of ice movement.

Fig 21 2 Glacial striae, Point of Maine.

In the course of glaciation, the side of a hill or prominence facing the direction from which the ice is advancing bears the brunt of abrasive attack. The result is often an asymmetrical form with the gentler slopes on the northerly (stoss) sides, and the steeper slopes on the southerly (lee) sides. Asymmetrical bedrock forms produced by glacial erosion are called *roches moutonées* (Fig. 21-3). *Roches moutonées* vary in scale from small ledges to hills of considerable magnitude. Because of the steeper slopes, soil is usually thinner and rock exposures correspondingly better on the lee sides of hills than on the stoss sides.

Locally, rock basins have been hollowed out by continental glaciers. The thousands of rock-rimmed lakes of glaciated regions

testify to the scooping action of the ice. In part, at least, the Great Lakes are of this origin. Three factors enter into the localization of glacial basining: resistance of underlying rock, concentration of ice flow guided by sub-ice topography, and local variation in load or movement of the ice itself. Perhaps most of the ice scoured basins may be ascribed to rock condition where either structural or lithologic weakness has served to localize deepening.

Fig. 213. Island in background is a roche moutonée. Boulder in foreground a glacial erratic. Frenchman's Bay, Me.

***Deposition.*** Nevertheless, whatever is moved by ice is deposited at greater or lesser distances from its starting place, and much of the load is soon dropped, lodged, or plastered along the way and overridden by the advancing ice. Some loose rock and earth is shoved along bodily at the bottom of the ice or in front of it, some is dragged along frozen fast at the glacial base or frozen within the ice; other debris rests on the glacier's surface or in basins of streams or lakes of ice water. When the ice wastes away, a part of its remaining load is deposited directly by the ice. Another portion, however, is further transported, sorted and then deposited by melt water. Two principal classes of glacial drift, therefore, can be distinguished: the unstratified deposits made directly by ice, and the stratified deposits made by glacial melt water. The name of the ice deposited debris is *till*, the name of the melt-water deposited material is *stratified drift*. Because

there are varying degrees of water assortment, however, till and stratified drift are not always easily or clearly separated.

*Till.* Ice moves essentially as a solid; it has no sorting power. A sand grain or clay particle moves along at the same rate as an adjacent fist-sized cobble or house-sized boulder. *Till*, therefore, is a heterogeneous mixture of ice-carried fragments of various sizes; its constituents are graded by neither size, nor shape, nor specific gravity. Because of grinding, crushing, and abrasion, most of the particles and fragments of till are angular in shape. The shape of the pebbles, however, is strongly influenced by their structure. Pebbles of shale, slate, or schist are usually flat; granite or quartzite fragments are usually blocky and angular. Some pebbles of till show various degrees of rounding because they were water transported during a part of their journey.

Most of the constituents of till are derived from local bedrock within a few miles of the deposit. Thus, in regions of massive crystalline rocks, as granite or quartzite, the till is largely made of coarse angular fragments, a *stony till;* in areas of sandstone or other friable rock, the till is dominantly granular, a *sandy till;* and in areas of weak rock, as shale or limestone, the bulk of the till is fine textured, a *clayey till,* or *boulder clay.* Most areas, however, are underlain by several types of bedrock, and some of the tougher rock types may travel many miles; consequently, the lithologic make-up of till, although reflecting the local bedrock, is a mixture of rock types.

Deposits of till give rise to a variety of topographic forms called *moraines.* Moraines are built along the margins of a glacier, hence with transverse ridge-like forms; or they are deposited beneath the ice and are without transverse linear elements. The former are *end moraines;* the latter are *ground moraines.*

*End moraines.* A glacier ends where forward thrust is overcome by melting. If the rate of melting is greater than the rate of ice advance, the margin of the glacier recedes; if forward thrust is more rapid than melting, the glacier advances. (Note: the expression "retreat" of the ice does not imply any reversal of ice movement.) If forward thrust and back melting are approximately equal, replacement from the rear is holding the line—advance balances retreat,

and the ice front is nearly stationary. At these times, material carried forward by the ice into the combat zone is dropped as the grasp upon it is loosened by melting. A till ridge is therefore formed along the margin. The balance of power, however, alternates, the ice front accordingly oscillates over a zone that may be several miles wide. Because of the oscillation, end moraines are usually belts of very irregular topography, composed of ridges and irregular knobs and hills of till. The outermost limits of ice extension may be marked by

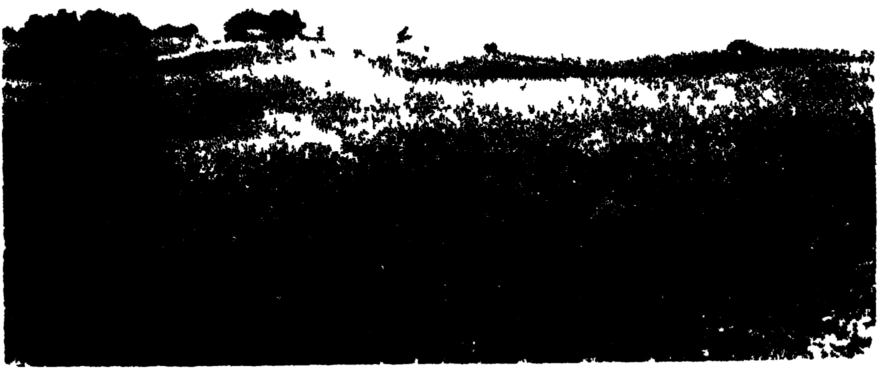


FIG. 21-4. End moraine, east central Illinois. Note lack of boulders and soft slopes. (Photograph by W. C. Krumbein, from 'Typical Rocks and Minerals in Illinois,' courtesy of Illinois Geological Survey.)

*terminal* moraines, provided the ice front was stationary long enough to permit their construction. End moraines built during general advance of a glacier are largely destroyed. During general ice retreat however, many stands may be taken, and *recessional* moraines built that are not destroyed. End moraines are thus terminal or recessional moraines.

Where composed of rocky and sandy till, end moraines are well defined with prominent knobs and ridges of steep slopes. Where composed of clayey till, end moraines are less well defined, with gentle slopes and subdued topography (Fig. 21-4).

End moraines are numerous and prominent in the Great Lakes states, where many individual morainic belts can be traced for miles. In New England, end moraines are patchy or lacking, perhaps because the bulk of the ice stagnated and melted away as an inert, motionless mass.

*Ground moraine.* During both advance and retreat of a glacier, till is deposited beneath and at the margin of the ice. These deposits are of irregular thickness, but are commonly thinner on the hills

FIG. 21-5 Bouldery ground moraine

than on the lowlands. The till sheet, deposited thus irregularly, is called *ground moraine* (Fig. 21-5) and is the most widespread of glacial deposits. Locally within till of the ground moraine are patches or areas of stratified (washed) material—sand or gravel. Although the ground moraine has no particular topographic expression, where thick it often has a somewhat undulating surface.

Most ground moraine is without well-defined topographic expression; however, locally, stream-lined hills of till, called *drumlins*, are found frequently in groups of hundreds. Drumlins are ice-molded parts of the ground moraine with the long axis parallel to the direction of ice flow. Many drumlins have steeper slopes on the stoss ends than on the lee ends; hence they have an asymmetrical shape, as shown in Fig. 21-6. In the discussion of erosion features,

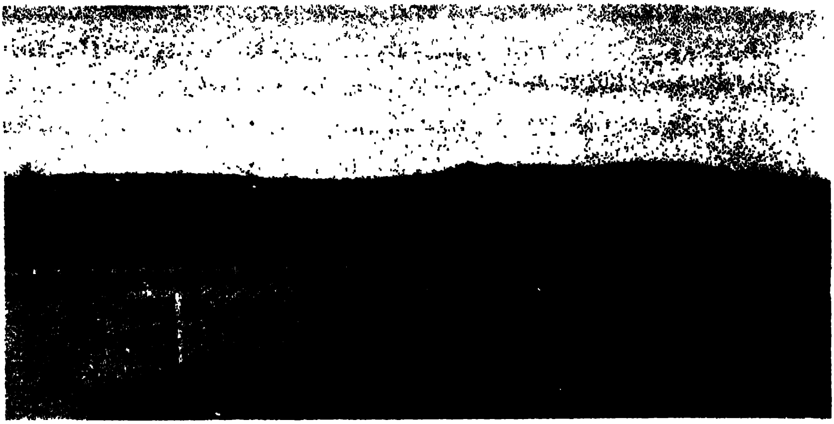


FIG. 21-6 A. Drumlin in longitudinal profile.

the asymmetry of *roches moutonées* with respect to direction of ice movement was noted to be the reverse of that of drumlins. In length, they range from a few feet to more than 2 miles, with heights seldom as much as 200 feet or widths as much as three-quarters of a mile. Although a few drumlins have been sculptured out of stratified drift and many contain lenses of sand and gravel, the bulk are till.

Drumlins appear to be the result of irregular accumulation be-

FIG. 21-6 B. Airphoto of Wisconsin drumlin. (Photo by C. C. Bradley, courtesy of F. T. Thwaites)

neath actively moving ice which overrides and shapes the till into stream-lined forms. Drumlin "fields," where closely spaced drumlins number hundreds, are found in west central New York, east central Wisconsin, and southern New England. Small groups and isolated examples of drumlins are much more widespread than drumlin "fields."

*Stratified Drift.* Deposits made by glacial melt water are known as *stratified drift, modified drift, aqueoglacial,* or *fluvioglacial* de-

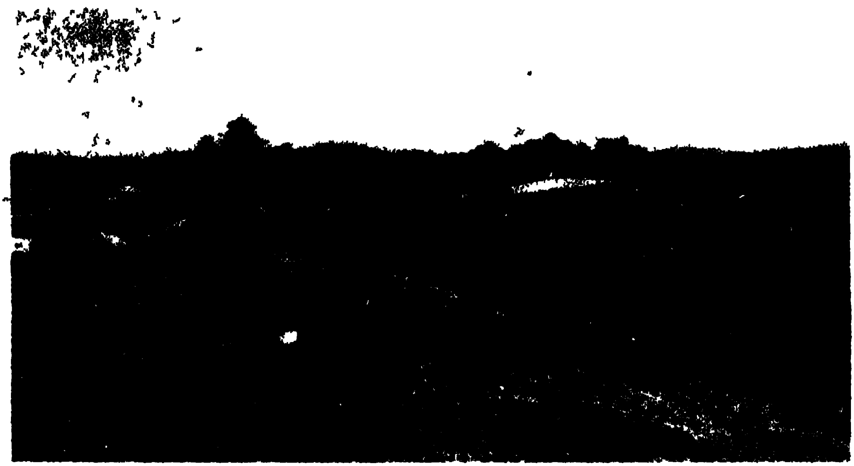


Fig 21 7 A Fsker

posits. Two requisites for stratified drift deposits are: a supply of till which can be carried and sorted by melt-water, and a check in velocity of the transporting melt-water current. Stratified drift, therefore, is deposited both in front of and behind the ice margin. Outside the ice margin or right against it, debris-charged melt-water that issues from the glacier builds alluvial deposits or supplies glacial sediment to marginal lake or sea; within the ice margin, ice-walled streams, lakes, and pools of melt-water deposit stratified drift.

Like till, from which it is derived, stratified drift is largely composed of rock fragments of local origin. The angular shapes of till fragments, however, are modified by water transport within short distances so that subangular to rounded pebbles predominate in

modified drift, The finer grade sizes, however, show less wear, and the sand and silt are commonly very sharp and angular.

The principal stratified drift deposits built within the glacial margin are eskers and kames; those deposited in contact with the ice margin are kames and kame terraces; and those deposited beyond the ice margin are outwash plains, deltas, and marine and lake silts and clays.

*Eskers.* Elongate ridges of stratified drift are called *eskers* or *crevasse fillings* (Figs. 21-7A and B*). These deposits are formed by deposition in drainage tunnels under or through the ice, in open channels in the ice, and in elongate re-entrants of the ice margin. Most eskers have a somewhat uneven crest line, and the longer ones have more or less serpentine courses. The similarity of esker pattern to stream pattern is well shown in the map of Maine eskers (Fig. 21-8). Branching of eskers is not as conspicuous, however, as the branching of streams. An *esker system* is made up of a number of individual esker ridges and individual knobs of stratified drift lined up to form a definite drainage pattern. An esker ridge may have a relief of as much as 150 feet above its surroundings, and individual ridges may be continuous for as much as 20 or more miles. The relief is more commonly on the order of 20 to 40 feet, however, and may be as little as 5 feet. Esker systems vary in length: the longest known can be traced with only slight interruption or discontinuity more than 150 miles. Most of the systems are much shorter. In cross-section, eskers are seen frequently to be very irregularly stratified. Also, in

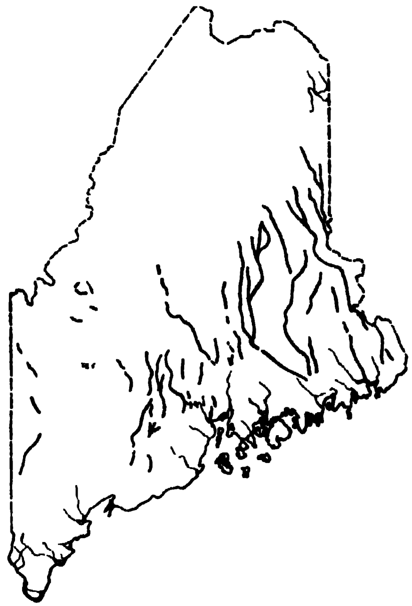
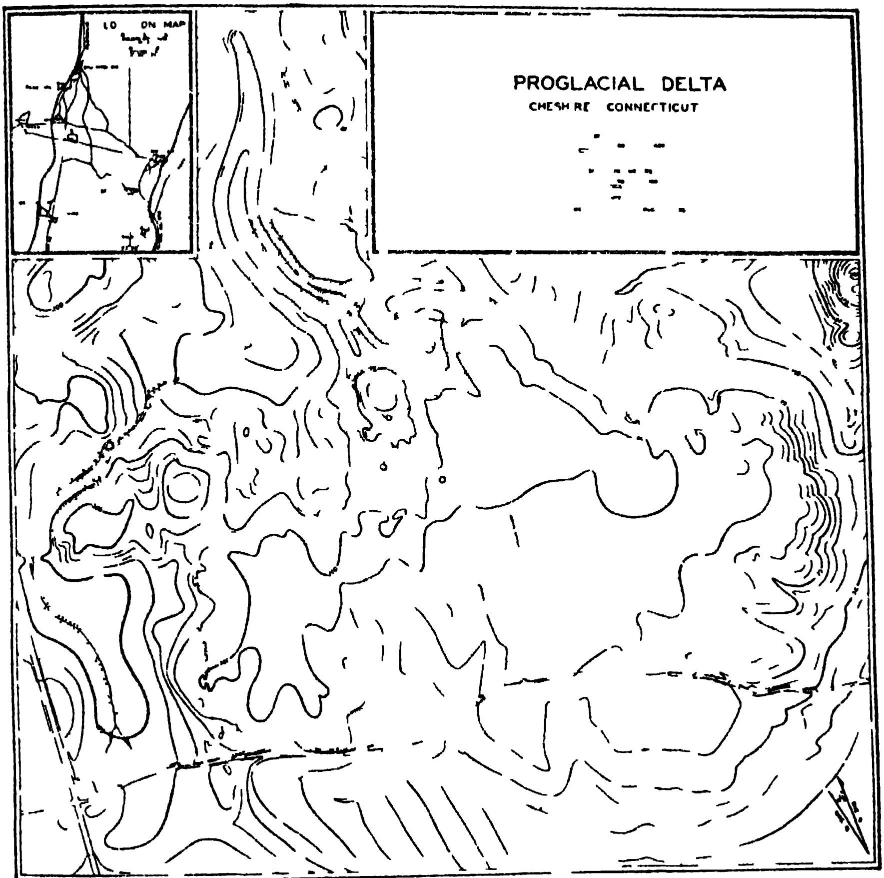


FIG. 21-8. Principal eskers of Maine. Note river-like pattern. (After E. H. Perkins, courtesy of Maine Technology Experiment Station)

cross-section, a roughly anticlinal like arching of the beds, due to slump when the ice retaining walls melted, is often noted. Because of rapid changes in the cross sectional areas of esker channels, loss or increase in water volume of the esker stream, and variation in




Courtesy R J Lougee

FIG 21 9

load of the esker stream, the mechanical composition or grading of an esker may change rapidly within short distances. Uniformity of pit-run material from eskers is not therefore to be expected. Commonly the steeper the side slopes of an esker, the coarser its gravel.

It is noteworthy that most eskers tend to follow low ground; thus,

the majority of eskers are found along river valleys. They often swing from one side of a valley to the other, and modern streams have frequently cut channels through the crossings. Eskers have supplied favorable sites for highways across swamps and other unfavorable terrain. They are excellent natural subgrades, well drained and free from frost heave. In northern New England in particular, where eskers are abundant, thousands of dollars worth of sand and gravel has been taken from eskers. A single air base, for example, required

FIG 21-10. Kame.

more than 1,000,000 cubic yards of gravel and sand, all of which was taken from local eskers.

*Esker deltas.* Locally where an esker stream terminated in standing water, either lake or marine, deltas were built. These have lobate outlines, and flat tops, although the tops may be somewhat pitted (Fig. 21-9). The grading of the material is generally more uniform than that of the eskers with which they are connected. Where cuts expose the cross-section, typical delta structure is seen (Fig. 18-7). Because they were built by glacial streams that were sub-

ject to great variation of discharge and sediment content, esker deltas are not so well graded as most stream deltas; they are, however, more uniform than eskers and frequently are more satisfactory sources of material.

*Kames.* Hills or knobs of stratified drift are called *kames* (Fig. 21-10). Though tending to be conical, many are of irregular shape. Some kames are deposited in *moulins* or holes in the ice. When the ice melts, the material slumps into mounds. Kames are also built at

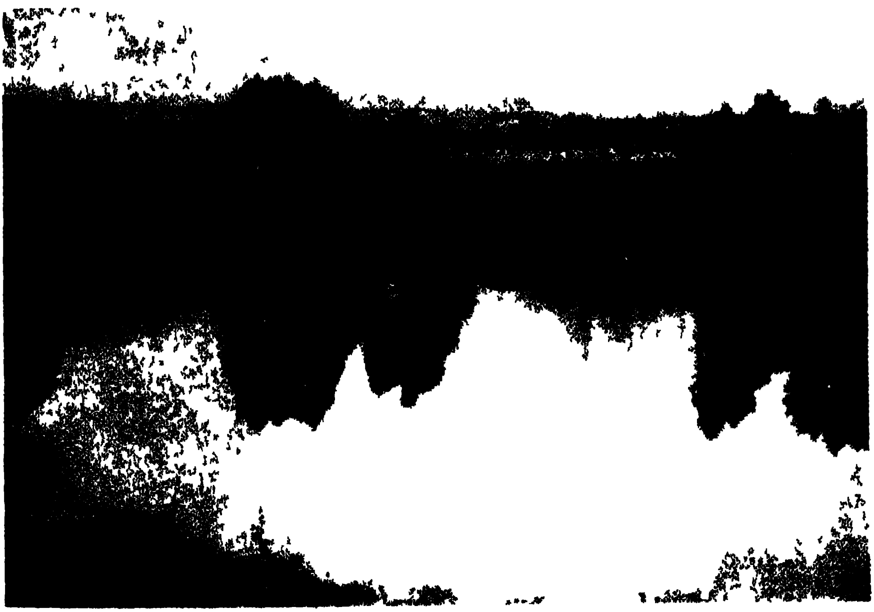


FIG. 21-11 A Kettle hole occupied by small pond

the margins of the ice, where melt-water deposits sediment in re-entrants and irregularities of the ice front. Locally, marginal kames are abundant enough to comprise a type of end moraine called *kame moraine*. Kames are also built where wasting ice becomes honeycombed with channels in which deposits are built around remnant ice blocks. As the ice finally wastes away, a topography of irregular knobs and hollows is left, called *kame* and *kettle* topography. The hollows are *kettle holes* formed where an ice block had been partially

or completely buried. When the ice block melts, a topographic depression results. Kettle holes are shown in Fig. 21-11. Kames vary in size from small knolls of a few feet in relief up to hills of 140 feet relief. Most of those shown on the topographic contour maps have a relief of between 20 and 60 feet. Most of them are less than a third

FIG. 21-11 B Kettle holes and associated kames (Courtesy of U S Department of Commerce, Civil Aeronautics Administration)

of a mile in diameter, and many are less than 600 feet in diameter Because of the turbulent and variable flow of kame-making waters the sorting is generally imperfect and stratification poor. A single kame, therefore, often yields material of widely variant grading.

*Kame terraces.* As the continental glaciers wasted away, ice

lingered longest in the valleys. At the lateral margins of a valley-remnant of ice, streams and lakes locally developed in which glacial debris was washed and deposited. Continued melting of the ice often uncovered lower outlets with the result that marginal lakes and streams were developed at progressively lower levels, leaving the previous deposits as terraces banked against the valley walls (Figs 21-12, 21-13). These deposits, because they frequently have pitted tops and somewhat hummocky outline, are called *kame terraces*. It

FIG. 21-12. Kame terrace. (Photo by I. H. Perkins)

is noteworthy that where kame terraces are found at several levels, step-like, along a valley wall, coarser and more crudely stratified materials are found in the upper terraces than in the lower terraces. Few kame terraces are more than 2 miles long, and most are shorter. The width is variable, but many are between 30 and 150 feet wide.

*Outwash plains.* Melt-waters, charged with debris, issue from glacial ice and deposit stratified drift. Where the debris-laden water spreads stratified drift over a broad area, it builds a deposit called a *wash plain*, or an *outwash plain*. Where an end moraine is under construction, the outwash forms a series of alluvial fans, or outwash plains, apexing at the places where the water comes across the mo-

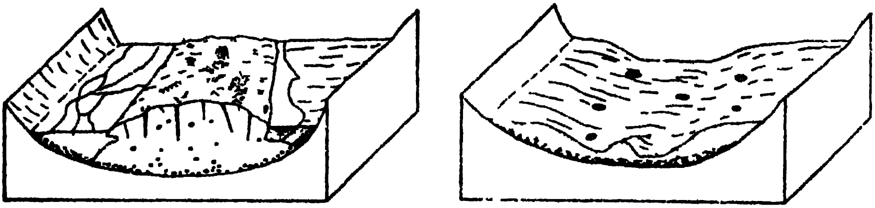


FIG 21-13 Origin of kame terraces (Reproduced by permission from *Glacial Geology and the Pleistocene Epoch* by R. F Flint, published by John Wiley and Sons, Inc)

raine. Commonly, the fans coalesce so that a single outwash plain covers considerable area. Across the outwash plain, channels are unstable; they shift back and forth because of rapid choking with sediment. Sediment is therefore spread more or less uniformly across the plain, and a comparatively level wash plain surface is built up The grading of wash plain material is generally good, the deposits are often very uniform. If the ice front was washed by lake or sea, the outwash is better graded and more uniformly stratified than if the ice margin stood on land. Because the velocity of the melt-water is first checked where it issues from the moraine, the coarser gravel is deposited near the moraine and grades out into finer material away from it. Locally, however, channels of coarse material, deposited by swiftly flowing currents may be traced across many wash plains, and the top few feet of gravel of many outwash deposits is coarser than the underlying portions. Accurate volume estimates of the coarse aggregate of a wash plain, therefore, require test pitting

FIG. 21-14. Pitted outwash near North Shapleigh, Maine

Many outwash plains are pitted with kettle holes (Fig. 21-14). These depressions are the result of melting of partially or completely buried ice blocks which were left either as isolated remnants during glacial retreat, or, if the ice front was submerged, were broken off and floated out from the glacial margin and were grounded. An outwash plain dotted with kettle holes is called *pitted outwash.* In locating test holes in pitted outwash, it should be remembered that the gravel is often coarser at a kettle margin than at a scant distance from the kettle.

Not only are outwash plains built in front of the ice, but many are built within the marginal zone of stagnant and wasting ice also. If an ice sheet stagnates, as happened over much of New England for example, it melts away like the winter snows of the present day. In spring, melting first uncovers the southern part of the area and progressively the "margin" of the snow blanket is pushed northward. However, there is no definite front or snow margin, for downward wasting bares many areas within the limits of the southern extent of the snow cover. Many wash plains thus are formed in deglaciation that are related neither to the ice "front" except that in a general way they are localized in the marginal zone, nor to end moraines. Many are deposits of temporary glacial lakes.

Because of their relatively uniform grading and large volume, outwash plains are one of the best sources of sand and gravel.

*Glacial-marine silt and clay.* During the process of ice erosion, a considerable amount of silt and clay sized particles was produced by grinding and abrasion. The relation between rock types and fineness of grinding has already been noted in the discussion of till. In northeastern America the level of the lands was lower with respect to sea level at the time of deglaciation than at present. Consequently, the sea flooded the valleys and lowlands as the ice cover melted away, and at many places the sea washed the ice margins.

Melt-water brought much glacially ground and pulverized rock into the marginal sea. The fine textured particles, silt and clay, settled out of suspension in the quiet water of the deeper or more sheltered places. A widespread blanket of glacial-marine clay and

silt was thus deposited over the lowlands. At many places the clay contains shells of types of animals still living along the present shores. One type of shell, *Leda*, is particularly abundant; hence, the clays are often called *Leda clays*. An arm of the Atlantic, called the Champlain Sea, extended far up the St. Lawrence Valley, hence the term *Champlain Clays* also is often applied to the glacial-marine clay deposits of the Northeastern seaboard. The inland extent of these marginal seas of late glacial time has not been fully established. In Maine, glacial marine clays are locally present up to at least 400 feet above the present sea level.

Typically, the glacial-marine clay is blue or gray and is known to most engineers as the *Blue Clay*, although at many places the deposits contain more silt than clay. Post-glacial weathering has locally altered the upper few inches or few feet of these deposits to an iron-stained brown or buff clay or silt much used in the manufacture of common brick. In some deep valleys, glacial-marine clay deposits are several hundred feet thick. The thickness is generally much less however, and marine clays and silts are lacking entirely at many places that were covered by the sea. The land was tilted as it emerged from the sea following the disappearance of the ice. The marine limit and, consequently, the upper limit of the silt-clay deposits, therefore, are not everywhere at the same elevation with respect to the present sea level. Along the northeastern seaboard the axis of tilt margins the northern shore of Long Island, the southern shore of Cape Cod, and extends through central Nova Scotia.

*Glacial-lake silt and clay.* Above the marine limits, much fine glacial sediment settled in the deep or quiet parts of numerous fresh water lakes which locally margined the ice. Fresh water does not flocculate clay as does sea water; hence, in these lakes, the silt particles settled out sooner than the clay particles. Much of the clay remained in suspension during the melting season; in winter, however, the surfaces of the lakes froze over, permitting the clay to settle. The deposits thus are commonly banded, and a pair of bands represents one year's deposition. The thickness of the individual layers varies from a fraction of an inch to several inches. A warm season

layer is generally coarser and lighter in color than a cold season layer. Seasonally banded clay is called *varved clay.* If a summer melting season was long and warm, the coarser and lighter member of the pair is thick; if the summer represented was short and cool, the summer layer is thin. Thus a climatic record of the time is presented by varved clay similar to that presented by the annual growth rings of trees.

*Summary of Deposits.* Two principal classes of material, *till* and *stratified drift* have been described as have also the principal topographic forms identified with each type. Table 21.1 presents a summary of glacial deposits.

### THE WORK OF MOUNTAIN GLACIERS

Mountain glaciers erode, transport, and deposit material in the same way as do the continental ice sheets. There are some results, however, that are characteristically of mountain glacier origin and which differ from effects produced by ice sheets. The erosional forms are more obvious and more scenic than the depositional forms.

***Erosion.*** Abrasion and plucking by mountain glaciers have added much to the variety and grandeur of mountain landscapes. The contrasts between mountains sculptured by local or valley glaciers and mountains not so modified is well shown by comparing the mountains of the southern Appalachian piedmont with those of the northeastern piedmont, notwithstanding that the latter region was also modified by continental ice invasions. The topographic detail of Mount Mitchell, North Carolina, for example, differs markedly from that of Mount Washington, New Hampshire.

Most mountain or valley glaciers occupy valleys that were initially cut by streams. In mountain areas, most stream valleys have the "V" of youth. An ice tongue pushing down through a "V" valley tends to modify the shape into that of a "U," generally with steeper side walls and a broader and flatter base than before glaciation. Base levels control the depths to which streams can cut. Mountain glaciers are not so limited. If they reach down to the sea, as in Alaska at the present time, downward erosion does not stop at sea

TABLE 21 1 *

CONDENSED SUMMARY OF DRIFT DEPOSITS AND TOPOGRAPHY

| Name | Topography | Material: Kind | Material: Sorting | Bedding | Confused with | Diagnostic features |
|---|---|---|---|---|---|---|
| Terminal moraine, stony | Ridge parallels ice border small knobs kettles irregular skyline "short hills | Till Sand gravel | None very poor | None sorted parts very irregular | Sand dunes gullies pitted outwash | Irregular skyline trend |
| Terminal moraine, clayey | Ridge parallels ice border smooth or gullied | Till | None | None | Ground moraine rock ridge | Trend |
| Terminal moraine, deltaic | Cones or mesa like hills ridges between kettles | Sand gravel silt | Very poor | Top horizontal inclined below | Outwash esker kame | Inclined beds trend level tops relation to standing water |
| *Roche moutonee* | Like drumlin but ends reversed | Rock | . | | Drumlin roc drumlin | Material form |
| Drumlin | Oval hill long axis parallels ice movement | Till | None | None | Esker roc drumlin | Material form |
| Ground moraine | Smooth gentle slopes except rock hills | Till | None | None | Terminal moraine lake deposits outwash | Material rolling topography |
| Outwash level | Flat terraces valley bottoms | Gravel sand | Good | Horizontal small cross bedding | Ground moraine lake deposits | Material sorting topography |

| | | | | | | |
|---|---|---|---|---|---|---|
| Outwash pitted | Kettles in flats or knob and sag with even skyline terraces | Gravel sand | Good | Horizontal slumped near kettles small cross bedding | Terminal moraine kames | Material sorting even skyline mesas |
| Esker | Winding interrupted ridge parallels glacial movement | Gravel sand | Poor | Irregular anticlinal cross section | Drumlin bar | Fresh material irregular top |
| Crevasse filling | Ridge high parts level top | Gravel sand silt | Good | Horizontal inclined or irregular | Esker | Top on same level as outwash or delta |
| Kame see stony moraine | Knolls kettles irregular [illegible] line | Gravel sand | P[illegible] | Irregular [illegible] | Pitted outwash terminal moraine | Material sorting bedding irregular skyline [illegible] |
| Beach | Shelf steep slope or cliff above slope below local kettles | Gravel sand boulders | Excellent to poor | Di[illegible] fr[illegible] of terrace | Accidental break in slope | Nearly level [illegible] st on headlands |
| Bar | Ridge curving level top rare kettles | Gravel sand | Ex[illegible] to poor | Ant[illegible] section | Esker | Excellent sorting level top |
| Lake bed | Flat gently rolling or[illegible] depressions | Clay silt sand | Excellent scattered [illegible] | Horizontal | Ground moraine outwash | Relation to topography clays silts varves |
| Subglacial wash | Rolling shallow depressions | Gravel sand stones | Poor to good | Irregular but undisturbed | Pitted outwash | Undisturbed bedding no flats |

* Reproduced by permission from 'Outlines of Glacial Geology' by F. T. Thwaites

level, because seven-eighths of the ice thickness must be submerged before the mass will float, relieving the bottom of scour.

As a main valley is deepened and broadened by ice erosion, the spurs between the tributary valleys that are characteristic of a stream drainage pattern are trimmed off. The tributary valleys are them selves modified by valley glaciers, although their lesser glaciers scour

FIG 21-15. Cirques, near Climax Molybdenum Mine, Colorado. (Courtesy of Caterpillar Tractor Co)

less deeply than the larger glaciers of the main valleys. When the glaciers disappear from the region, therefore, many tributary valleys are left hanging. Bridal Veil Falls, Yosemite, is a classic example of a hanging valley. Although hanging valleys are formed in other ways also, they commonly signify glaciation.

The heads of glaciated mountain valleys are often amphitheater like gouges in the mountainside which have steep side and head walls and relatively flat floors. These are called *cirques,* (Fig. 21 15) and many are occupied by lakes. Cirques are evidently the result

of glacial sapping and plucking. In lofty mountain regions that have been subjected to prolonged alpine glaciation, cirque growth has resulted in the production of serrated knife-edges between cirques and of angular mountain forms. Such peaks as the Matterhorn, for example, illustrate this kind of sculpture.

A valley glacier erodes most actively in the upper and middle portions of its valleys; near the lower end of the ice, erosion is less because the ice is melting and thinner and may be carrying an excessive load. An active valley glacier may discover local differences in resistance to erosion—weak rock types or fractured zones. These

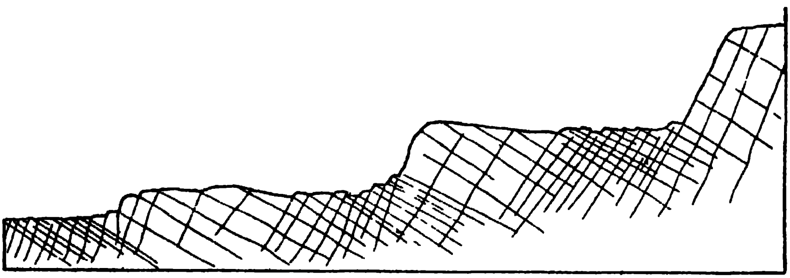


FIG. 21-16. Longitudinal profile of glaciated valley. (After F. F. Matthes, U. S. Geological Survey)

less resistant parts are deepened (Fig. 21-16). The concept of temporary base levels which was developed for stream erosion does not hold for ice erosion; consequently, the longitudinal profiles of many glaciated valleys differ from those of normal stream valleys. Many lakes are found in formerly glaciated valleys. Some are dammed up behind deposits, as moraines, which the ice left behind as natural dams; others occupy rock basins that were scoured out by the ice.

***Deposition.*** As a result of erosive activity, mountain glaciers pick up material from the sides and bottoms of their valleys. Material also is added by landslide and avalanche from adjacent slopes. Because there is much shearing of active ice over slower moving or stagnant portions, rock debris is raised into the middle or upper parts of a glacier. At the lower terminus of the glacier, if the forward thrust is approximately balanced by back-melting, coarse and fine

material alike may be dumped in the form of irregular ridges and knobs, *end moraines*, which loop around the end of the ice tongue. Morainic ridges, also, may be built where till is lodged between the ice and the valley wall; when the ice melts these are left as *till terraces* or *lateral moraines*. The junction of two mountain glaciers is often marked by the coalescence of the two inside lateral moraines to form a *medial moraine*, as shown in Fig. 21-1. *Ground moraine* is also deposited along the valley behind the end moraine.

Material washed by melt-water, stratified and sorted, is deposited in front of the end moraine as *outwash*. The outwash, confined by the valley walls, often extends for a considerable distance down valley. An outwash fill is often called a *valley train*. In glaciated valleys alluvial fills may be of considerable depth. The melting of the ice furnishes much material which may be washed into depressions scooped out by the ice; and lakes and basins in advance of the ice margin may be filled. In the Yosemite, the depth of valley fill is locally 900 feet.

## The Ice Age

The earth is just emerging from a period of refrigeration that affected all continents, although northern North America, northern Europe, and northwestern Asia were the only areas which were extensively buried by ice sheets not now in existence. By the enumeration and correlation of varves of fresh water glacial clays and silts, by estimation of the length of time necessary to cut such post-glacial features as the Niagara gorge, and by estimates based on the rate of weathering and dissection of the most recent till sheets, inferences have been made as to the lapse of time since the disappearance of the continental ice sheets from North America and Europe. The most generally acceptable estimate, some twenty thousand years, shows the relatively short span of post-glacial time. The ice age, called by geologists the *Pleistocene epoch*, had a duration perhaps on the order of a million years. The geography of ice distribution and the complexities of ice advance and retreat have been partially worked out; the causes of a glacial epoch are as yet uncertain.

***Geography and Extent of Ice.*** In North America, during the Pleistocene, there were four centers of ice accumulation from which ice pushed outward in all directions. From east to west these are: the Labrador, Patrician, Keewatin and the Cordilleran centers. Ice from the Labrador center spread widely over the northeastern part of North America; it reached west to the shores of Hudson Bay and Lake Superior, south to the Ohio River and Long Island, and east to the Atlantic. At its maximum extent, ice from this center covered approximately 3,500,000 square miles. The Patrician center was minor, compared to the Keewatin and Labrador centers. It was located south of Hudson Bay, in northwestern Ontario. The Keewatin center was located southwest of Hudson Bay. From this center, ice pushed west to the Rockies, south to the Missouri River, and east to the Lake Superior region, covering more than 1,500,000 square miles. The western cordillera of Canada was another center of dispersal, the Cordilleran Center. In this mountainous region there was an extensive development of mountain and piedmont glaciers which coalesced to cover much of the area between the Rockies and Coast Range, British Columbia, and the Yukon. Some 350,000 square miles were glaciated from this center. The map of Fig. 13-3 (page 273) shows the centers and extent of glaciation for North America.

Northern Europe, like North America, was widely overspread by continental glaciers during the Pleistocene. Approximately 2,000,000 square miles, including the British Isles, Norway, Sweden, Finland, North Germany, the Baltic States, and northern Russia east of the Urals were covered at the time of maximum glaciation. Over Europe, the ice seems to have spread from one center called the Baltic or Scandinavian center. From the Alps, valley glaciers extended to form piedmont glaciers in Austria, Italy, and France; the Pyrenees and Appenines also had mountain glaciers.

The Pleistocene ice over Antarctica was probably thicker than at present. Although none of the other lands had continental ice sheets, all had mountain glaciers which were more numerous and extended to lower levels than at present. Australia, where no glaciers exist

today, had mountain glaciers; and on New Zealand mountain glaciers were very active. In Africa, Mt. Ruwenzori and Mt. Kilimanjaro had glaciers 3000 to 4000 feet lower than at present. In South America, conditions were similar to those of Africa, in that evidences of greatly lowered snowlines and more extensive mountain glaciers are abundant. In Patagonia, piedmont glaciers covered a considerable area, extending some 300 miles east of the mountain front. Although in Asia lower thermometer readings than anywhere else on earth have been recorded, Pleistocene ice sheets were limited to northwestern Siberia where some 1,600,000 miles were glaciated.[1] No evidence has yet been presented for extensive Asiatic ice sheets. The mountain glaciers, however, were more extensive and came to lower levels. Possibly the relatively small extent of continental glaciation during the Pleistocene in Asia is in large part explained by aridity.

***Complexity of the Ice Age.*** The Pleistocene epoch is estimated to have lasted about a million years. Glacial ice did not prevail all of this time, however, over the northern parts of North America and Europe. There were, rather, a series of advances of continental glaciers, separated by interglacial stages during which milder climatic conditions prevailed. The major advances and retreats have been established by the recognition of different till sheets superimposed one above another, and by the discovery between till layers of buried soil horizons which carry remains of temperate and even subtropical vegetation. In the northeastern part of the United States, multiple glaciation has not been clearly established, although several sets of glacial striae have long been known. On Long Island and in the Middle West the sequence of ice invasions has been clearly worked out. In both North America and Europe, at four separate times within the Pleistocene, continental ice sheets made major advances which were followed by climatic amelioration. Evidence for this fourfold division of the ice age is found on both sides of the Atlantic.

[1] Flint, R. F., *Glacial Geology and the Pleistocene Epoch*, Wiley, New York, 1947 p. 352.

It is interesting to note that consolidated glacial deposits of vastly greater age than the unconsolidated deposits of the recent ice epoch are known. Beds of consolidated till, *tillite*, containing striated boulders, and resting on striated and glacially polished ledges, clearly are ancient glacial deposits. Deposits of this type, on the order of two hundred million years old, record the greatest of glaciations yet worked out in the history of the earth; they have been found in South Africa, Australia, Brazil, and locally in North America.

***Causes of a Glacial Epoch.*** A variety of causes have been suggested to account for glacial epochs. Some hypotheses, which have been based upon astronomical cycles, call for periodic glaciation. So far as evidence of past glaciations has been collected, it appears that glaciation has been recurrent but not periodic. Other theories have been based upon drastic changes of the earth's poles or shifts of the earth's land masses with respect to the poles. Large-scale polar shifts appear to be dynamically impossible, and large-scale continental drifting not yet demonstrated. Such shifts in any event do not satisfactorily account for glacial epochs. Changes in the proportions of atmospheric gases have also been invoked, particularly of carbon dioxide. Changes of elevation, too, have been called upon, although evidence of changes of the necessary magnitude in recent geological time have not been presented to the general satisfaction of geologists. Further, the output of solar energy is held to have been variable by some, thus accounting for cold periods of history.

The truth, when it is finally arrived at, may include elements of several of the current hypotheses. This much, at least, can be said: (1) The surface temperatures of the earth are dependent upon solar energy; and the energy output of the sun does vary in a not strictly periodic way as measured over a relatively brief span of years. (2) The surface temperatures of the earth are related to elevation; and the most obvious explanation of submarine gorges and canyons of late geological date is that they were cut by subaerial streams. If this is their origin, the lands recently have been several thousands of feet higher relative to sea level than at present. (3) Astronomical cycles that would affect surface temperatures, to some degree at least,

do exist, but of themselves they have not been sole causes of glaciation. Perhaps a conjunction of causes is necessary; a conjunction that is not periodic but that has been recurrent.

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# CHAPTER XXII

# GEOLOGIC INTERPRETATION OF TOPOGRAPHIC MAPS AND AIRPLANE PHOTOGRAPHS

The features of the earth's surface are determined by geologic processes working upon geologic structures.

—Douglas Johnson

THE DIRECT APPLICATION OF TOPOGRAPHIC CONTOUR maps and airplane photographs to such engineering problems as route surveys, reservoir and dam locations, flood control, irrigation and drainage planning, and many others including the construction of maps from airplane views, is obvious. Less obvious but of high significance are the geologic interpretations possible from these representations of topography. The surface features of the earth, which collectively comprise the physical landscape, are the result of two reciprocally acting sets of forces: these generated principally by the sun, extraterrestrial forces; and those generated within the earth, terrestrial forces. The extraterrestrial forces are the surficial agents of gradation, the most important of which are wind, water, and ice. The earth-born forces are those of diastrophism, which cause upheaval, folding, and faulting, and those of igneous activity which result in extrusions and intrusions. The operation and effects of these forces have been considered in preceding chapters. This present discussion sketches some of the deductions possible as to the nature of land forms, their component materials, and geologic structures from study of maps and airplane photographs. Optimum use of either maps or photographs requires considerable

experience and training. Especially does it require a knowledge of the geologic processes and their effects.

The practical uses of map interpretation are highly diverse. Reconnaissance surveys of soil conditions and suitabilities, for example, are greatly speeded by intelligent use of map and photograph. Because the engineering characteristics of the various soil types can be generalized (Table 5.2, page 74) a recognition of soil type distributions from air views or from topographic maps may save much in engineering effort, time, and expense. It should be emphasized, however, that although many maps and photographs yield much information, engineering practice calls for detailed and quantitative data. Map and photograph interpretations, therefore, guide and direct ground and field work; they cannot replace it. Material reconnaissance by photograph and map interpretation, is aided and made more precise by limited sampling for control. This is true whether for foundation conditions over extensive areas, as for airport or highway location, or for construction materials. Indeed, for any but the broadest generalization, a program of limited sampling is essential to successful map and photograph interpretation.

Any engineer concerned with soil and rock welcomes survey methods that speed the work and yield reliable results. In recent years the application of airplane photographs to material surveys consequently has been widely accepted.

### Characteristics of Contour Maps and Aerial Photographs

Topographic contour maps are necessarily generalizations. Henry Gannett,[1] for many years Chief Topographer of the topographic branch of the United States Geological Survey, says: "Whatever its scale may be, every map is a representation reduced from nature, and consequently there is more or less generalization. It is, therefore, impossible to make any map an accurate, faithful picture of the country it represents." In generalization it is essential to preserve those details of highest significance and to omit those of

[1] Gannett, Henry, "Manual of Topographic Methods," *U. S. Geol. Survey Bull.* 307, p. 84.

least consequence. The recognition of topographic features and their significance, i.e., a geological comprehension of the landscape, is essential to good topographic mapping of any but very limited areas. The possible uses of the map depend in large measure, therefore, upon judgment and skill of the topographic engineer responsible for the map. The difference between good and poor contouring is well illustrated by Fig. 22-1 from Douglas Johnson.[2] In Fig. 22-1A the details of contouring show clearly the cirques, hanging valleys,

FIG 22-1. Examples of good and poor contouring. Note that in the right-hand figure the index forms of the alpine glaciation, the characteristic forms of the cirques, hanging lateral valleys, and U cross-section of main valley are lost or obscured. (After Douglas Johnson. Reproduced by permission from *The Principles and Practice of Surveying*, Vol. II—*Higher Surveying*, by Breed and Hosmer, published by John Wiley and Sons, Inc.)

and broad U-shaped valley floors characteristic of alpine glaciation. In Fig. 22-1B generalization is carried so far that most of the essential characteristics are lost or obscured. The inner light by which one of the topographers saw evidently was of weak candlepower.

In contrast to topographic contour maps, airplane photographs portray all the minute and intimate detail of the area. The clarity of the detail, of course, depends on the quality and scale of the photograph. The disadvantages, as compared to contour maps, are the multiplicity of detail, lack of elevations, and the fact that they are not true maps. However, for some purposes the detail is ad-

[2] Breed and Hosmer, *Higher Surveying*, 6th Ed N. Y. 1947, p. 303.

vantageous. Stereopairs show relief much more graphically than do the contour maps and greatly assist in interpretation. For many phases of geologic interpretation, therefore, airplane photographs are superior to maps.

***Contour Maps.*** Contour maps are familiar to most engineering students, and, although many have had some experience in making them, a brief review of some of their features is presented before indicating certain types of geologic interpretation. The best-known and most accessible contour maps are those prepared by the United States Geological Survey. They may be purchased directly from the director of that organization.

*Contents.* Three principal categories of representation are included on these maps: culture, hydrography, and relief features. Culture includes roads, railroads, houses, bridges, boundaries, and other works of man. Cultural features are shown in black. Hydrography includes streams, lakes, fresh and salt water swamps, and other water bodies. Hydrography is printed in blue. Relief features which comprise the surface configuration, are indicated by contour lines, printed in brown. Theoretically every point of a contour line is at the same altitude with reference to some datum plane, usually mean sea level. The contour lines, spaced at equal vertical intervals apart, thus show the shapes of hills, mountains, valleys, cliffs, closed depressions and other topographic detail. In addition, the more recent maps show the principal automobile routes in red, and on some maps wooded areas are shown in green.

*Scales.* The scale of the map is the ratio between a unit distance on the map and the corresponding horizontal ground distance. Thus, fractionally expressed, a unit map distance constitutes the numerator and the corresponding ground distance, *expressed in the same units,* constitutes the denominator. For example, a scale of 1:63,360 means one map inch to the horizontal ground mile (63,360 inches). Because a contour map is a horizontal projection, map distances are shorter than the corresponding ground, or slope, distances according to the relief of the map. Fractional expression of scale, since it is a ratio, holds for whatever units of measurement may be

applied. The larger the value of the fraction representing the scale, the larger the map scale; thus, large scale maps are those on which a unit map distance represents a comparatively short ground distance. Scales are also indicated graphically by lines divided into units that represent the distances marked along the scale line. Maps that are to be enlarged or reduced should have graphic scales.

*Orientation.* The orientation of the map is shown by latitude and longitude lines. True astronomical north and magnetic north are shown on the map margin by arrows, and the angle between these directions, the magnetic declination, is stated.

*Accuracy.* Mathematical precision is not an attribute of contour maps. On most contour maps the elevations at the crests of hills and ridges, at the bottoms of valleys, and at abrupt changes of slope are those that have been most accurately determined in the field survey. The contours for the most part are interpolated and sketched, hence the accuracy depends largely on the skill of the topographer. Ordinarily, the error in reading elevations from contour maps is less than half the contour interval. Horizontal measurements are closely determined and closely controlled.

***Aerial Photographs.*** The two types of airplane photographs most commonly used are *verticals* and *obliques.* Verticals, or vertical views, are taken with the optic axis of the camera vertical; obliques are taken with the optic axis of the camera tilted from the vertical. Obliques are called *low obliques* if the horizon does not show in the picture, or *high obliques* if the horizon does show. Verticals are preferred if the photograph is to serve as the basis for map construction, although the obliques can be rectified. *Mosaics* are patch-works put together from several overlapping individual photos taken at different camera positions. They may either be corrected or uncorrected. Controlled mosaics approach maps, but even these fall short of the accuracy of scale and direction of good planimetric maps.

Collimating marks are shown on the edges or corners of most photos. Lines connecting opposite collimating marks intersect at the center of view. Half-arrows are the most common collimating marks, although other types of mark are also used. Numbers at the

corners of the view identify the individual photograph according to the filing system of the concern producing the photos. Usually the date and frequently the time of day are indicated. Altitude of flight and focal length of camera are often recorded; less commonly the average scale is marked.

*Contents.* On airplane photographs, as on contour maps, cultural features, hydrography, and relief are shown. Shapes, distribution patterns, and differences in shade tones bring out these features on aerial photographs and, in addition, much that is not shown on conventional topographic maps.

Cultural features, generally, can be distinguished by form or pattern and by associations. Most works of man have either angular or smoothly curving outlines or patterns. Natural patterns are less geometric. Association of features frequently give clues to specific identification; a common association, for example, is graveyard and church. Hydrographic features are rather readily recognized by form and pattern as well as by shade tone. Streams, lakes, and sea commonly photograph black, unless light reflection from them was directly into the camera at the time the picture was taken. If the water surface does reflect light directly into the camera the water body photographs white, or light. Disturbed water surfaces give varying shade tones. Dry stream courses or lake beds photograph light. The direction of stream flow can usually be told from the angle at which tributaries enter and by asymmetric bulges on the downstream sides of meander loops. Swamps and wet areas appear on photographs as dark patches, irregular in outline. Relief can be most easily and surely seen by stereoscopic study of paired photographs. It can be inferred, however, from the hydrographic patterns, and also from the shadows cast by relief features.

In addition to those three classes—culture, hydrography, and relief which can be distinguished on both contour sheets and airplane photographs—the latter show much cultural detail and distribution patterns and variations of vegetation, soil, and rock.

***Scale.*** On vertical photographs the average scale can be expressed fractionally as:

$$\text{Scale (R.F.)} = \frac{f}{A}$$

where $f$ is the focal length of the camera in inches, and $A$ is the altitude in inches. This representative fraction, or fractional scale is reduced to unity by dividing both terms by the numerator. The formula scale is valid for photographs taken in level flight over level ground. The scale can be determined also by field measurement between two ground points established from the photograph; or it can be established by comparison with a good map of known scale. The line chosen for either ground measurement or map comparison should pass near the center of the photograph. Corrections for parallax are unnecessary for most geologic uses of the photographs; however, if a map is being compiled, parallax corrections are necessary.

In obliques, scale varies from place to place on the photograph. The scale does not vary, however, along any one line parallel to the axis of tilt of the camera, although each of these lines parallel to the tilt axis differs in scale from any of the others.

***Orientation.*** The compass orientation of airplane photographs, if not known, can be established in several ways. One method is to choose two sharply defined and easily identified map points that can be located on the ground and to determine the direction of the ground line between them. Another method is to establish compass direction by comparing the photograph with a sufficiently detailed map of the area. Approximate orientation can be determined also if the time of day when the photograph was taken is recorded by the direction of shadows. Most commercial air photographs are taken between 10 A.M. and 2:30 P.M. On many photographs if the flight was north-south the photograph number is in the northeast corner: if east-west in the northwest corner. *A photograph should be placed in position for study so oriented that shadows in the picture fall toward the observer; the light source should be from the front.*

Aerial photographs are not precise maps. Variations in flight altitude, in tilt of camera, and in elevation of ground surface contribute to distortion of distance and direction. They are accurate.

however, in the presentation of minute detail. Every object that can be seen from above is shown with the fidelity of camera and film

## Geologic Interpretations

Not every contour map or aerial photograph can be interpreted geologically, and there are all gradations from those which yield little to those which can be rather fully read. In all cases, familiarity with the region aids in interpretation. Many students expect to find the gamut of geological information on each map or photograph. Such maps or photographs, of course, are never found. Skill in interpretation comes with experience and, in particular, increases with that type of field experience which calls for critical analysis of land form, for example the field search for clay or gravel. The co ordinate use of airplane photographs and contour maps of the same area rapidly develops skill in map interpretation.

Both depositional and erosional features tell something of the geology of an area. In the following discussion, interpretation of surface features is briefly reviewed Subsequently some elementary evidences of geologic structure are pointed out

***Wind.*** Deposits of the wind are sand dunes and loess. Dune areas are readily recognizable on many maps and photographs. Loess deposits are more difficult to identify. Wind erosion forms are not commonly identifiable on either contour map or aerial photograph

*Dunes.* Sand dunes are found typically along lakes and seashores along some stream valleys, and in the dry regions. Most dunes are small. The relief of dunes varies from a few feet to more than 100 feet, although few dunes catch more than two or three contours on a 20-foot contour interval map. Diameters are usually on the order of a quarter mile or less. Elongate dunes, parallel to lake- or sea shore, may be several miles in length, but are commonly interrupted by irregularities of deposition and blow-out.

Irregular small hills and associated depressions, elongate ridges localized along a shoreline, crescentic dunes (barchanes), and comb shaped hills are the most readily identifiable forms. Intermittent lakes occupying associated depressions are not uncommon, but, for

the most part, sand dune areas do not have many lakes or ponds. Well-defined drainage patterns are absent. Rain readily penetrates the permeable sands, hence a surface drainage pattern is not developed. Figs. 22-2A* and B represent a dune area by contour and also by an aerial view of dune topography. On photographs, sand areas unless covered with vegetation commonly appear in light gray shade

FIG. 22-2 B. Sand dunes and blow-outs. (Royal Canadian Air Force)

tones or white. If they support vegetation, this is usually of uniform type within a given region and is in contrast with the vegetation of less well-drained and less uniform soils. Wind-blown sands are well graded, uniform, and fine grained. The windward slopes are usually gentle, whereas the lee slopes are steep. In a region of variable winds, however, the difference in slopes is not distinctive.

*Loess.* Wind-blown silt derived from dry areas, from flood plains, and from glacial outwash is called *loess*. Loess deposits are difficult

to pick out on topographic maps unless the scale is large and the contour interval small. Two characteristics aid in the identification of loess. The first is an elongate, streaky pattern that is frequently prominent. The parallelism of low loess ridges is illustrated in Fig. 22-3A. The second is a rather typical erosion pattern that is formed because loess is a noncohesive soil and stands in steep slopes. Long, steep-walled gullies, often subparallel, have tributaries which

FIG. 22-3 A. Loess ridges. (Courtesy of U. S. Department of Commerce, Civil Aeronautics Administration)

enter at high angles; the tributaries in turn are indented by lesser gullies of fin-like aspect. The erosion pattern, as shown in Fig. 22-3B, is rather distinctive. On the ordinary 1:62,500 topographic map with a 20-foot contour interval, loess is seldom safely inferred. The thinner the loess and the rougher the topography, the less surely can it be identified on either map or photograph.

*Glaciers.* Both erosional and depositional forms of glacial origin can be identified on maps and photographs. The effects of alpine glaciers, namely, cirques, hanging valleys, U-valleys (as well as certain

other features), are strikingly shown. The effects of continental glaciers also, although less spectacular, may be identified with considerable assurance. The principal deposits are: ground and end moraines, outwash plains, eskers and esker deltas, kames, and kame terraces. Erosion by continental ice sheets is principally noted in the "rounding" of hill and ridge forms. This rounding, due to the

FIG. 22-3 B. Erosion pattern in loess. Note the short deep gullies and the right-angular drainage pattern. Dry region U. S Department of Commerce, Civil Aeronautics Administration, Technical Development Report No. 52, by Jenkins, Belcher, Gregg, and Woods. (See reference at end of chapter)

carving of convex rather than angular slopes, is especially useful as an index of continental glaciation.

*Ground Moraine.* Most ground moraine has no definite topographic expression of its own. Indeed, the very lack of systematically arranged forms aids in its identification. Undrained depressions, many of which are occupied by lakes or swamps; stream courses that appear more or less haphazard, without definite pattern; and many slopes that are unrelated to drainage lines signify ground moraine. In addition, the presence of rounded hills or ridges and the identi-

fication of other glacial features, for example eskers, give support to the interpretation. Fig 22-4 * illustrates ground-moraine topography

A particular variety of ground moraine, the drumlin, is easily identified by its elongated oval and smoothly molded form.

*End Moraines* End moraines are the deposits formed at the margins of ice advance Because the fronts of continental glaciers fluctuated back and forth over a marginal zone, small ridges and hills of irregular outline form morainal belts Depressions are associated in large number with most morainic belts. The many irregular hills and depressions locally resemble sand dune topography Ridge like elongations, distribution as a belt independent of sand source and abundant small water bodies help to distinguish morainic topography from dune topography Many, but not all morainic belts have outwash plains in front of them, as shown in Fig 22 4 * The identification of associated outwash plain, kettle holes ground moraine, or other glacial deposits confirms the morainic character of the belt. The individual knobs and ridges are rarely as much as 100 feet in relief

Materials composing moraines are *till* The clayey tills have lower slopes and flatter forms Swamps and lakes imply high water table and impermeable material beneath In glaciated regions the impermeable material is often clayey till Steeper more pronounced slopes are indicative of stony tills If the character of the bedrock can be inferred from the topography inferences can be drawn as to the nature of the till For example granite hills in most instances indicate a rocky till sedimentary rocks indicate that the tills of ground and end moraine are probably sandy or clayey. Till deposits tend to be thinner and coarser on the upper slopes and hills than on lower slopes and lowlands

*Stratified Drift* Outwash plains are distinguished by their relatively smooth surfaces and by their relation to morainic topography Many outwash plains, however, are pitted with kettle holes Pitted outwash, for the most part means that the deposit was built by receding ice, and that the associated moraine was built as a recessional rather than as a terminal moraine

*Eskers* are long, sinuous sand and gravel ridges. They are unique and easily recognized on map or photograph. They are knobby and frequently discontinuous. *Kames,* of somewhat similar origin and composed of similar material, are irregularly rounded hills which seldom occur singly. Eskers vary in length from a few tens of feet to many miles. They seldom exceed 100 feet in relief. Kames are roughly equidimensional, rarely more than 60 feet in relief or as much as a third of a mile in diameter. *Esker deltas* were built where glacial streams discharged into sea or lake. They are relatively flat-topped and are lobate in outline, as shown in Fig. 21-9 (page 516). The surfaces of many are pitted with kettle holes. *Kame terraces* are irregular, somewhat knobby forms found along the walls of glaciated valleys. Locally they are found as a series of steps; if so, the higher terraces are more irregular of form and are made of coarser, less uniformly graded gravel than the lower terraces. Fig. 22-5 shows the appearance of kame terraces.

***Streams.*** Stream deposits are readily identified by their flat surfaces and by their position with respect to streams. Extensive flood plains of large, slowly flowing streams are composed of silt or silty clay. Those of smaller extent, associated with rapidly flowing streams, are made up of coarser material. Natural levees backed by flood plain and swampland are particularly conspicuous. Meander scars and abandoned channels, also, are especially obvious on many flood plains and are unmistakable features of many maps and photographs as shown on Fig. 22-6.

River terraces margin many streams. In glaciated regions they are particularly abundant. Both alluvial terraces—composed of gravel, sand, or silt—and rock terraces are present. The former are often more fragmentary and less continuous than the rock terraces. The dissection pattern may aid in the distinction between them. Terraces composed of the finer alluvial materials may be somewhat gullied at the terrace margin. Sand and gravel terraces or rock terraces, however, are generally undissected. If terraces flank both sides of the stream continuously at corresponding elevations, they


Fig. 22-3. Glaciolacustrine terraces, Quinnipiac Valley, Connecticut. Ruled areas are the terraces; the unruled strip between the terraces, the river channel, and the unruled strips outside the ruled areas are till-covered bedrock. (From R. F. Flint, courtesy of Connecticut Geological Survey)

are probably rock terraces. Nevertheless, the distinction between the types is often difficult or impossible without field examination.

River bars, which if extremely numerous give the stream the braided aspect seen in Fig. 22-7 * as well as deltas, are readily apparent on maps and photographs. The greater the gradient of the stream, the coarser the material making up the deposits. The shoals

FIG. 22-6 Meander scars and filled in oxbow lake (U S Dept. of Agriculture)

of channel crossings and other parts of the stream, although not seen on contour maps, are readily picked out on photographs.

Alluvial fans, especially well-developed deposits flanking mountain areas in semi-arid lands, are easily recognized. Alluvial plains built by the coalescence of piedmont fans have arcuate contours related to the streams that build them. Alluvial fans are composed of gravel, sand, and silt. The coarsest material is found in the higher parts of the fan.

Stream erosion patterns, as seen on maps and photographs, are

of significance because both structural and lithologic inferences can be drawn from them. The major stream patterns are, in general, conditioned by the lithology and structure of the bedrock. Minor or micro-patterns are to a large degree determined by the composition and texture of the regolith. Discussion of structural and lithologic interpretations of bedrock is deferred to a later section of this chapter (page 552). Some inferences as to soil types, drawn from dissection patterns, however, are given here.

Permeable soils—gravel, sand, and to a lesser extent silt—which have gently sloping surfaces develop little or no surface erosion pattern. In contrast the impermeable soils, principally of the clay group, have surface run-off which results in the development of a stream or gully pattern. Because of ready permeability, sand and gravel soils even on steep slopes suffer little dissection. Kames and eskers, for example, have almost entirely escaped sculpturing since they were formed some fifteen or twenty thousand years ago Locally, however, these coarse soils have been gullied. The common erosion form is the short, steep-walled, "U" gully. The drainage texture is comparatively coarse. *Drainage texture* means the spacing of the streams or gullies. The dissection pattern of loess (silt) has already been pointed out. The drainage texture of silts is somewhat closer meshed than that of sandy soils. Clays and clayey soils, on the other hand, show characteristically a fine drainage texture. The slopes are "soft" rounded slopes, with a maze of branching open "V" gullies readily detected on photographs and good contour maps as illustrated in Fig. 22-8. The difference in dissection between sand and clay can be seen on a minute scale in sand and clay banks or fills. Abandoned brick-clay excavations, for example, frequently present miniature bad-land topography.

Soil texture and type can be deduced from airplane photographs by other methods than those just described. Land use, as pictured on airplane views, may give a clue to soil drainage, hence type. For example, orchards require fairly well-drained soils; examples could be multiplied. Vegetation, although difficult to interpret, may give reliable indications of soil condition; wet or dry situations, for

example, can often be determined. Variations in soil shade tone are also indicators, and if field sampling on a limited scale establishes the significance of the shade variations, accurate deductions as to soil type distributions may be made. An excellent report on soil identification with special reference to airport and highway engineer-

FIG. 22-8. Glacial till plain. The dark areas are plastic silty clay; the light areas are more silty and drier. Note the soft slopes and relatively fine-textured drainage pattern characteristic of clayey terrain. (Courtesy of U. S. Department of Commerce, Civil Aeronautics Administration)

ing has been prepared by the Civil Aeronautics Administration of the U. S. Department of Commerce.[3]

***Ground Water.*** Evidences of ground water are confined to areas underlain by some soluble rock, usually limestone. The principal topographic form which results from ground water work is the *sink*

[3] Jenkins, D. S., Belcher, D. J., Gregg, L. E., and Woods, K. B., "The Origin, Distribution, and Airphoto Identification of United States Soils," *Tech. Development Report No. 52,* U. S. Department of Commerce, 1946.

*hole*. Sink holes are depressions of greater or lesser depth. Many are mere sags resembling glacial kettle holes. Others are steep-sided rock-rimmed depressions of considerable depth. Some are more than 300 feet deep and many are 20 to 50 feet deep. Roughly circular in plan, they vary from a few feet to a few hundred feet in diameter Many sinks contain small ponds. If the limstone lies in horizontal

FIG 22 9 Karst topography Note relatively few surface streams and many sinks (Courtesy of U S Department of Commerce, Civil Aeronautics Administration)

position, at or near the surface, sink holes are distributed throughout the area. Some areas have sink holes only in the lowlands or along valleys. It may be deduced from such a distribution that the up lands or hills are capped with an insoluble rock If the sink holes are distributed in linear pattern, it may be inferred that the lime stone is folded; the rows of sinks follow the limbs of the fold.

*Karst topography* is illustrated by Fig. 22-9. A karst area can be likened to a stone sieve; rain-water passes through the sinks and

circulates underground. Consequently little or no surface drainage develops. The boundary, therefore, between a karst-limestone area and one underlain by some other type of rock often can be approximated by study of the map or photograph.

***Lakes and Seas.*** Lake and sea coasts display various readily recognizable deposits and erosion features. Most of these are so obvious on map or photograph as to require no comment. It may be well, however, to mention that airplane photographs are advantageously

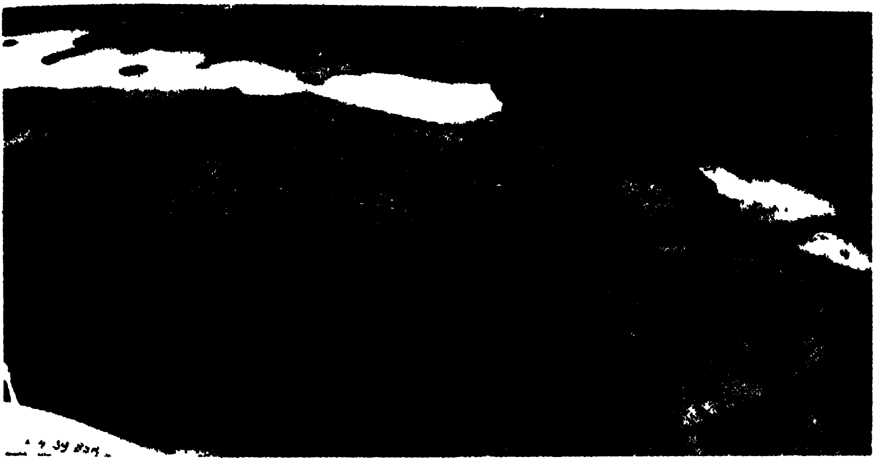


FIG. 22-10A Elevated Beach Ridges. (Royal Canadian Air Force)

used by the engineer concerned with shoreline changes. The migration of littoral zone sediments and localization of deposition and erosion can be readily determined by a comparative study of photographs taken at different times.

Marine and lake deposits are found miles away from present sea- and lakeshores. They were built at times of past higher water levels. Recognition of these forms is of particular value in regions otherwise devoid of good construction material. Beach ridges, now high and dry, are shown in Figs. 22-10A and B.* Hills that were once islands may have wave- or current-built appendages of sand or gravel. A drumlin in Maine, for example, has a hooked spit attached which has yielded much good gravel, although the material of the drumlin


FIG. 22-11. (Canadian Geological Survey)

itself is practically worthless. The deposit was first recognized by study of the contour sheet.

***Gravity.*** Earth movements in mountainous areas often can be recognized by landslide scars, which on aerial photographs are easily discerned. On topographic maps recognition is more difficult. On some maps, however, as shown in Fig. 22-11, contours clearly show the slides. Landslide material usually shows an irregular hummocky

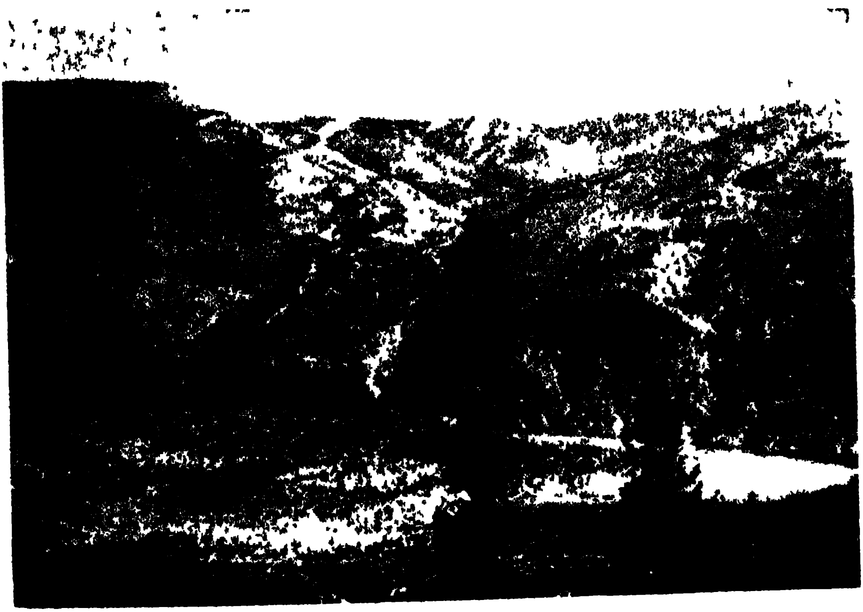


Fig. 22-12. Slumgullion mudflow, responsible for San Cristobel Lake, Colorado (U. S Geological Survey)

surface. A line of depressions at the base of a steep slope, especially if hummocky topography is associated on the down-slope side, suggests landslides. Locally, streams have been dammed by earth movements, forming lakes as shown in Fig. 22-12 and, locally, valleys have been narrowed. Deflection of the stream by slide or flow may be detected where slide scars are lacking. Sod-cracks, which appear as dark lines roughly parallel to surface contour, and "cat-steps," or terraces, can be detected on some photographs. These indicate creep; they do not appear, however, on contour maps.

Because slide or flow material is so frequently troublesome in engineering practice and, in particular, is dangerous material for dam foundation or abutment or as a site for highway location, engineers are well advised to study carefully the phenomena of earth movement.

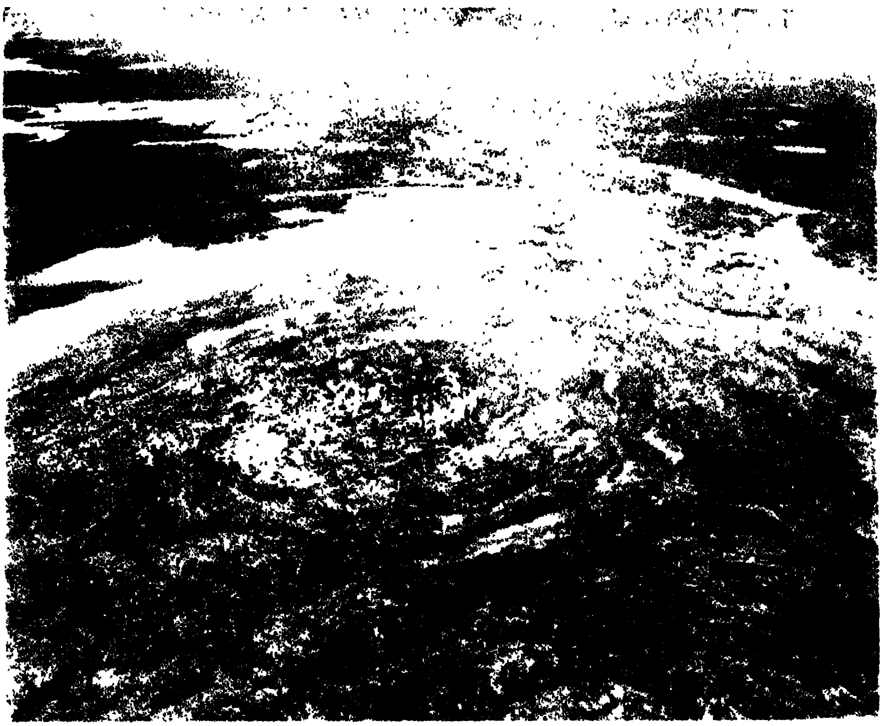


FIG. 22-13. Airphoto of structural dome. Note tendency for concentric drainage. (Royal Canadian Air Force)

## TOPOGRAPHIC STRUCTURAL EXPRESSION

In many regions, structures of the underlying bedrock are reflected in the topography. The primary cause for topographic expression of structure is the difference in resistance to weathering and erosion displayed by adjacent rock types. Resistant rocks are etched in relief; weak rocks are worn into valleys and lowlands. The weathering and erosion processes concerned, the state of reduction

(topographic age) of the surface, and the structures affected determine the topography. Without differences of rock resistance, however, topography would be structurally meaningless. Folds, faults, and igneous activity bring adjacent rocks of different resistance into the domain of weathering and erosion; furthermore, faults and joints may weaken the rock or localize erosion. The erosion pattern, consequently, through the distribution and character of both negative and positive relief features, gives indications of underlying structure. In other words, both drainage patterns and hill or ridge patterns are useful in structural interpretation of topography.

***Folds, Hogbacks, and Cuestas.*** In many areas of folded or tilted rocks comprised of a series of alternating resistant and nonresistant layers, the streams assume a trellis pattern. Indeed, this pattern indicates adjustment of streams to structure and resistance. If the folds making up the structure plunge, the subsequent streams may be deflected about the noses. If the structure is that of a dome or basin, subsequent valleys may be roughly concentric (annular) about the structure. Fig. 22-13 shows a structural dome.

Folding and tilting are recognizable on maps and photographs by the ridge and hill pattern. Fig. 22-14* shows a looped ridge. Because the north slope of the nose of the western loop is long and gentle, the structure is inferred to be a northerly plunging anticline. The nose of the adjacent loop to the east slopes off rather abruptly to the south. This part of the structure, consequently, is inferred to be a northerly plunging syncline.

If resistant rock ridges are asymmetrical, the more steeply sloping sides commonly face away from the dip direction. Asymmetric ridges are well illustrated in Fig. 22-15;* the dip is inferred to be westerly. Asymmetric ridges are called *hogbacks*. Structures similar to hogbacks but with gentle back slopes are called *cuestas*. A cuesta thus consists of a steep erosion escarpment, or cuesta face, and a gentle back, or dip, slope. Cuestas are found in areas of gently dipping rocks and indicate the direction of regional dip. The cuesta of the southerly dipping Niagara limestone, for example, can be traced across much of the northern part of New York State and far

beyond through the lake states into Canada. There are, of course, many other types of escarpment.

In addition to the criteria mentioned, folding can often be detected on airplane photographs by the outcrop pattern, which on some pictures can either be seen directly or inferred from vegetation patterns.

***Faults.*** Faults are difficult to detect on topographic maps. If the faulting is recent, fault scarps may be distinguished. A *fault scarp* is the abrupt slope or cliff produced by the dislocation itself, not greatly modified by erosion. Most fault scarps are comparatively straight, whereas most other regional escarpment types, cuestas for example, are sinuous. Only very recent faults display fault scarps, however, for erosion quickly destroys the form. If rocks of unequal hardness have been brought together by faulting, a *fault-line* scarp often develops by the wearing away of the softer rocks along one side of the fault. Fault-line scarps, consequently, may face either in the same or opposite direction as the original fault scarp. Because they are erosion forms and are themselves dissected by erosion, fault-line scarps, as seen on maps and photographs, are frequently indistinguishable from other types of scarp.

Stream dissection or erosion of fault scarps gives rise to triangular facets which terminate the spurs of the uplifted mass, as was shown diagrammatically in Fig. 9-18 (page 190). In nature, of course, these truncated spurs are not so clearly triangular in shape; however, careful observation in many instances will reveal their character. Fig. 22-16,* for example, suggests the probability of a fault marginal to the mountainous area.

Faults are more easily detected on airplane photographs than on contour sheets. Fig. 22-17, for example, illustrates faulting very clearly. On photographs, topographic breaks transecting the strike of beds and rectilinear boundaries between adjacent areas that contrast with each other in structure, in topography, in vegetation, or in soil shade suggest faulting. Angulate drainage patterns, also, suggest fracturing, although not necessarily faulting.

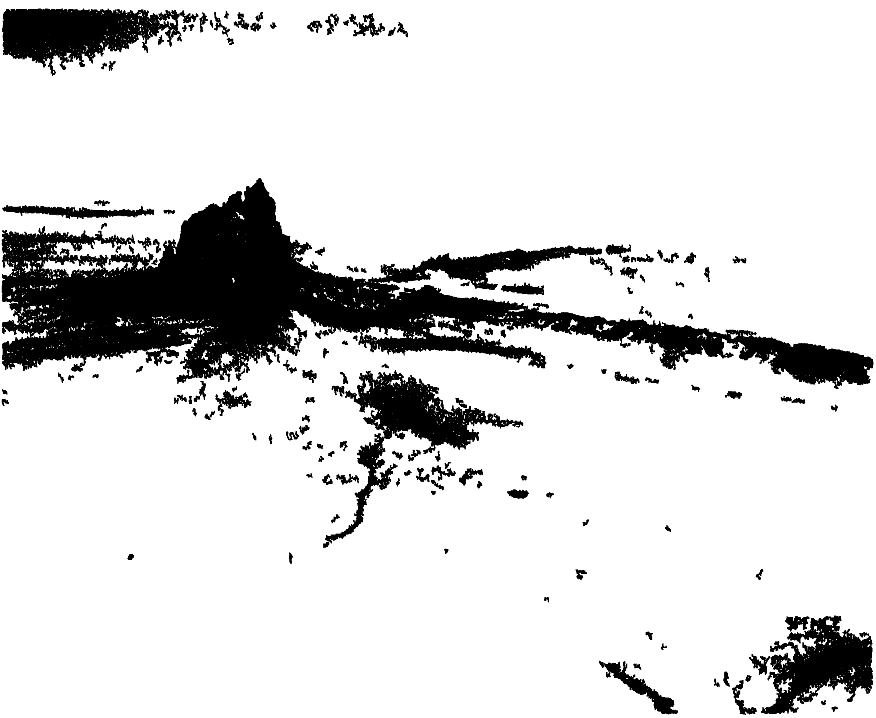
The maps and photographs of some areas show rectilinear patterns of drainage and relief. In some instances the fractures themselves can be seen on airplane photographs where given prominence by weathering. Fig. 22-18* illustrates rectilinear patterns. Erosion has been controlled or directed by the fractures, which may be either or both joints and faults.

FIG. 22-17. Airphoto of fault. (Royal Canadian Air Force)

***Igneous Intrusions.*** Igneous intrusion forms rock in many places that is more resistant than the rocks into which the intrusion is made. Inequalities of resistance are often sufficient, therefore, to develop recognizable topographic forms. Locally dikes make prominent wall-like ridges as shown in Figs. 22-19A and B.* On airplane views this topographic form can be more certainly identified than on the contour maps, for in many photographs they can be seen to transect structure. Sills are less certainly identified than dikes because

they are similar in topographic form to the ridges of more resistant strata of a sedimentary or metamorphic sequence.

Large intrusions, as stocks or batholiths, stand up in relief in many areas. Although they, themselves, may be considerably modified, a contrast in erosional detail, trend of valleys and ridges, and



Spence Air Photos

FIG 22 19 A Volcanic neck and radiating dikes, New Mexico

type of slope frequently permit ready identification on either photograph or contour map. Large intrusions are mostly localized in regions that have been strongly folded. Although many are elongate in the direction of prevailing strike, they commonly weather into rounded hills which contrast with the elongate strike ridges so frequently displayed by the associated rock. Fig. 22-20 shows a granite intrusion, the margin of which can be rather closely approximated

## TOPOGRAPHICAL MAPS

The references in the text to the following colored maps are marked with a black star (*).

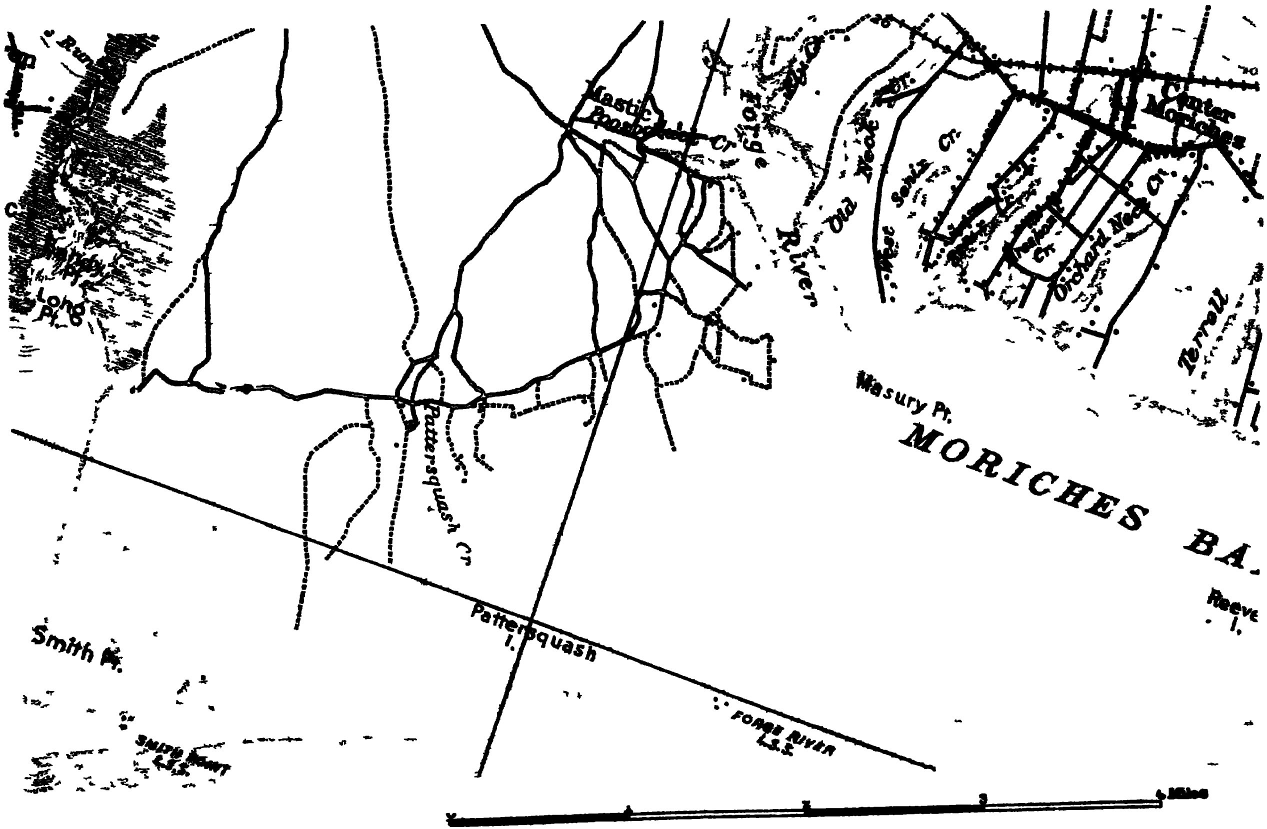



Fig 20 11 An offshore beach inclosing a lagoon Note the drowned streams (U S Geological Survey)

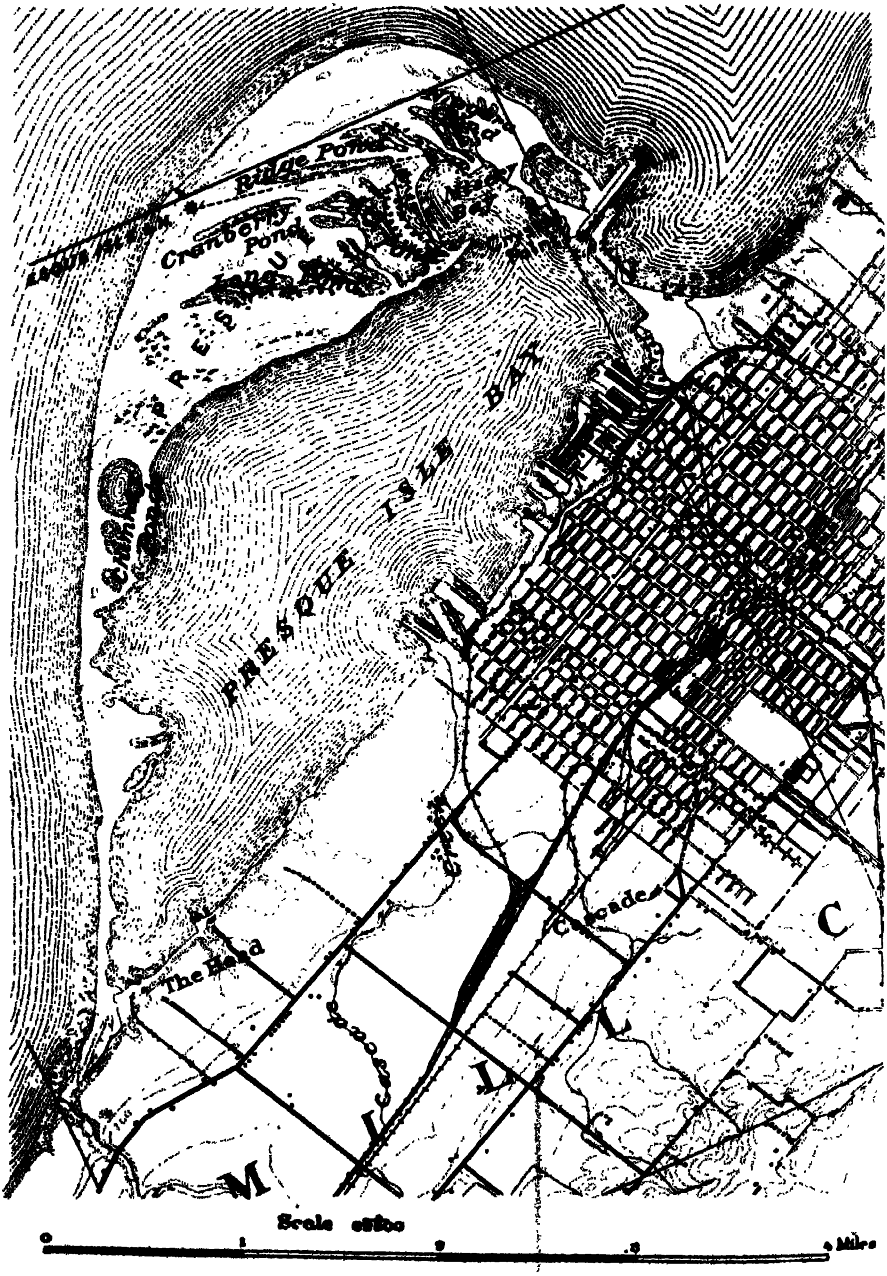



FIG. 20-13. A hook at Erie, Pennsylvania. (U. S. Geological Survey)

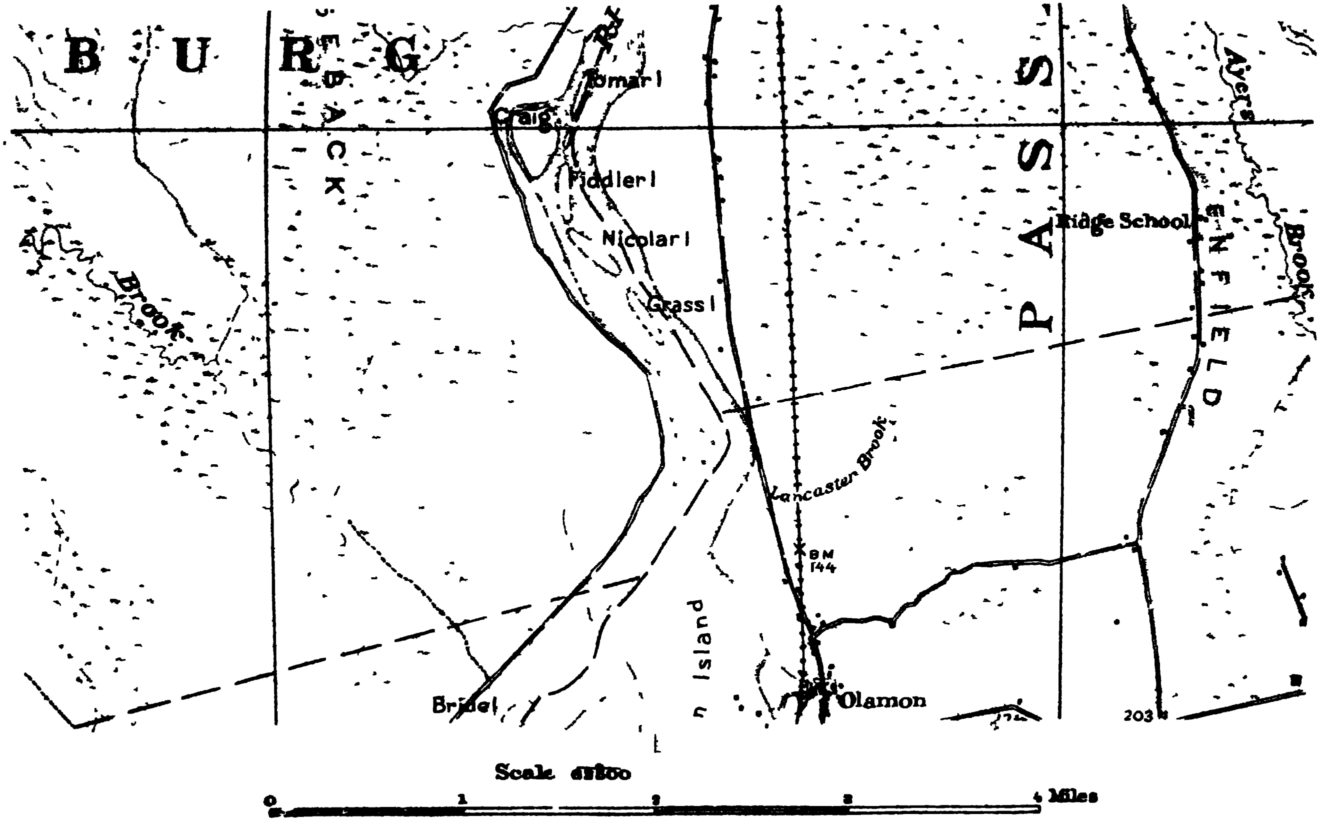



FIG. 21-7 b A contour map of eskers, showing three well defined eskers and many kames. (U. S Geological Survey)

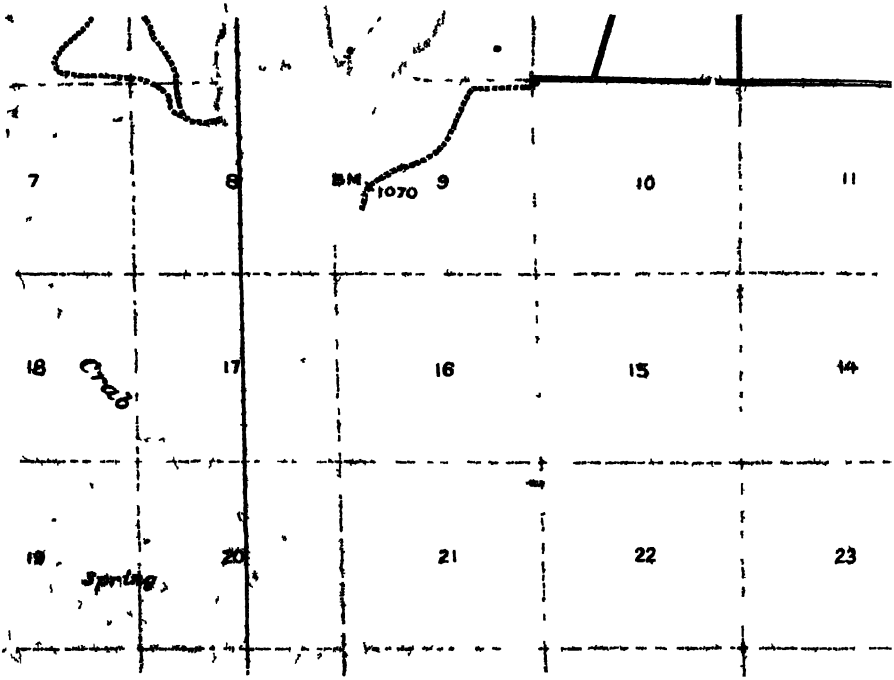



FIG. 22-2 A. Sand dunes and blow-outs. (U. S. Geological Survey)

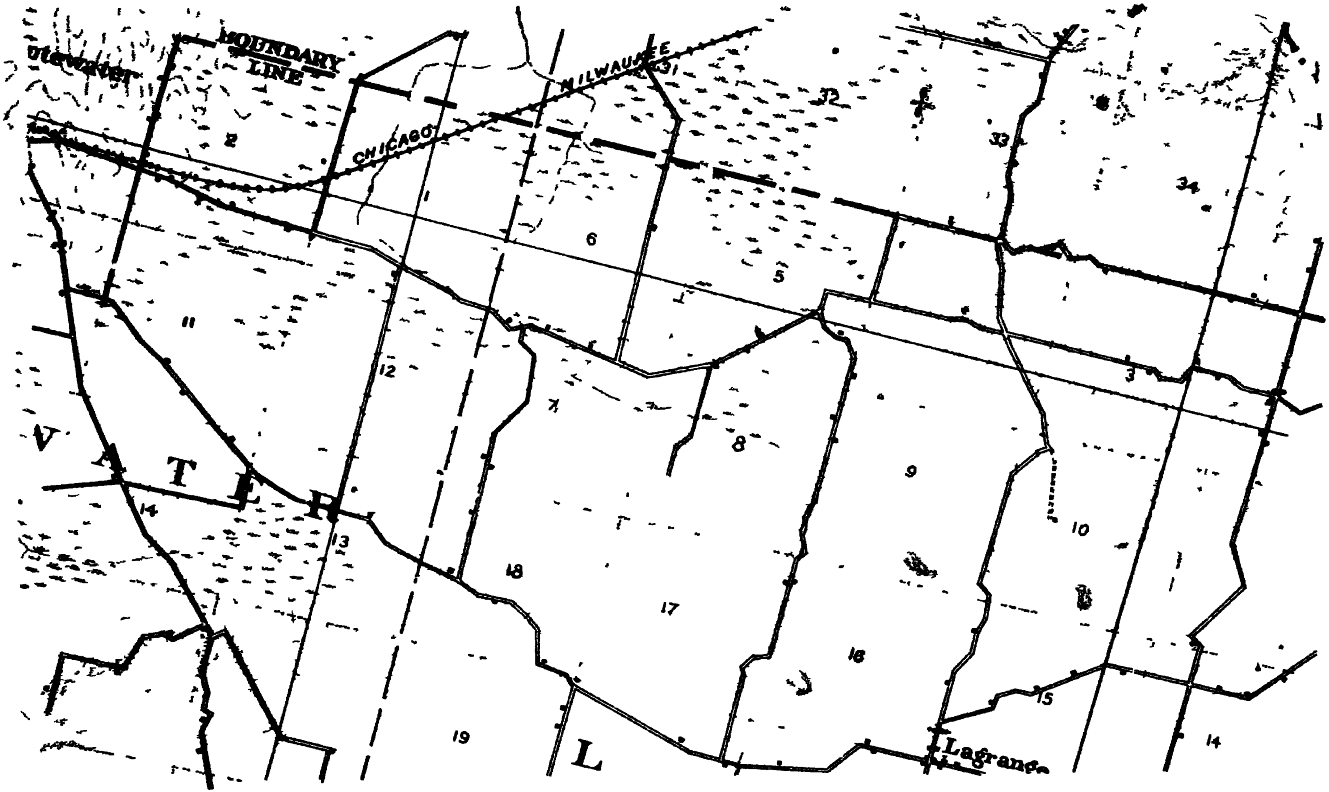



FIG. 22-4. Ground moraine, end moraine, and outwash plain. In the upper left are drumlins. The belt of knobs and ridges extending from lower left to upper right is the end moraine in front of which is an outwash plain pitted with kettle holes. (U. S. Geological Survey)

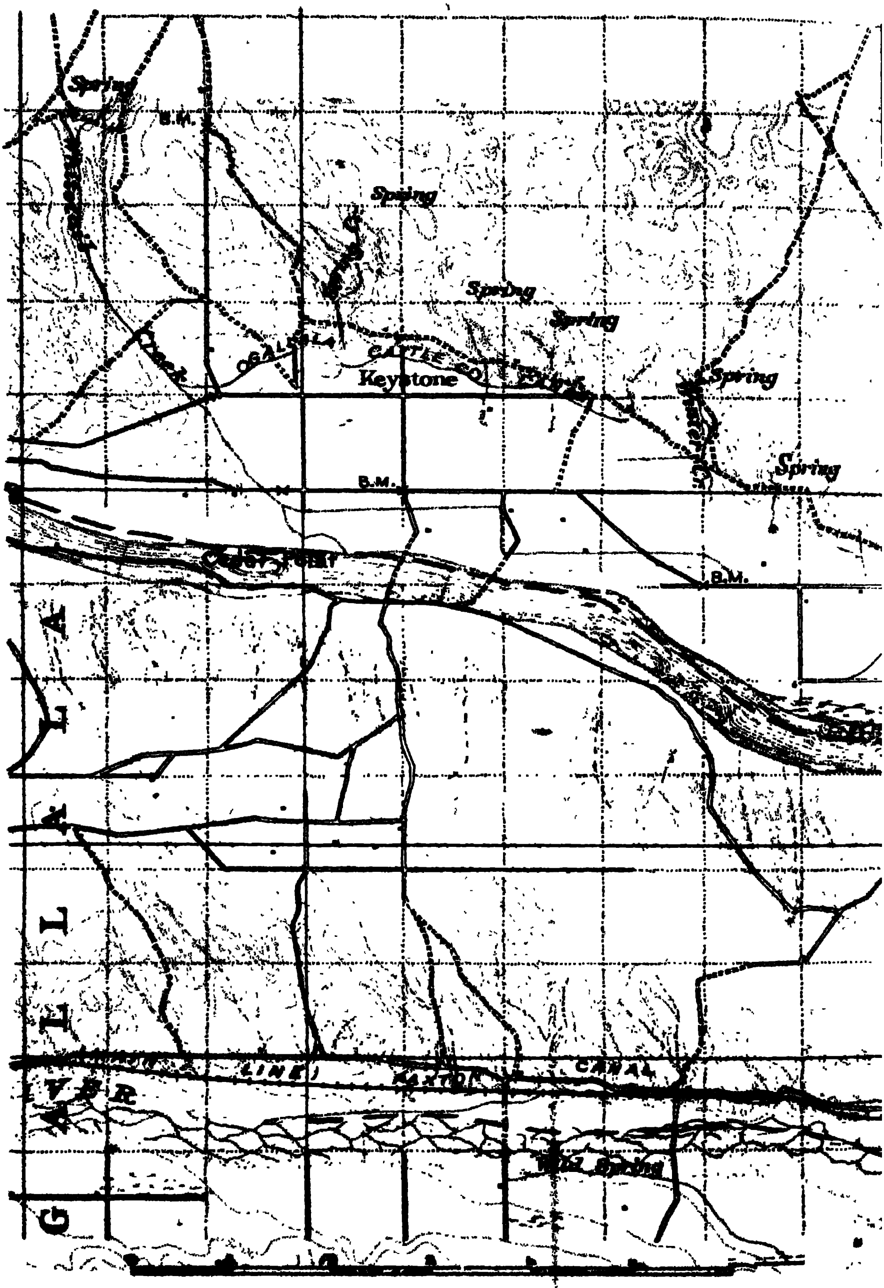



FIG. 22-7. A braided stream, just east of Ogallala, Nebraska. Much of the water o the South Platte moves through the channel deposits. The discharge of the North Platte is only about 15 per cent greater than that of the South Platte. Note the sand dune topography. (U. S. Geological Survey)

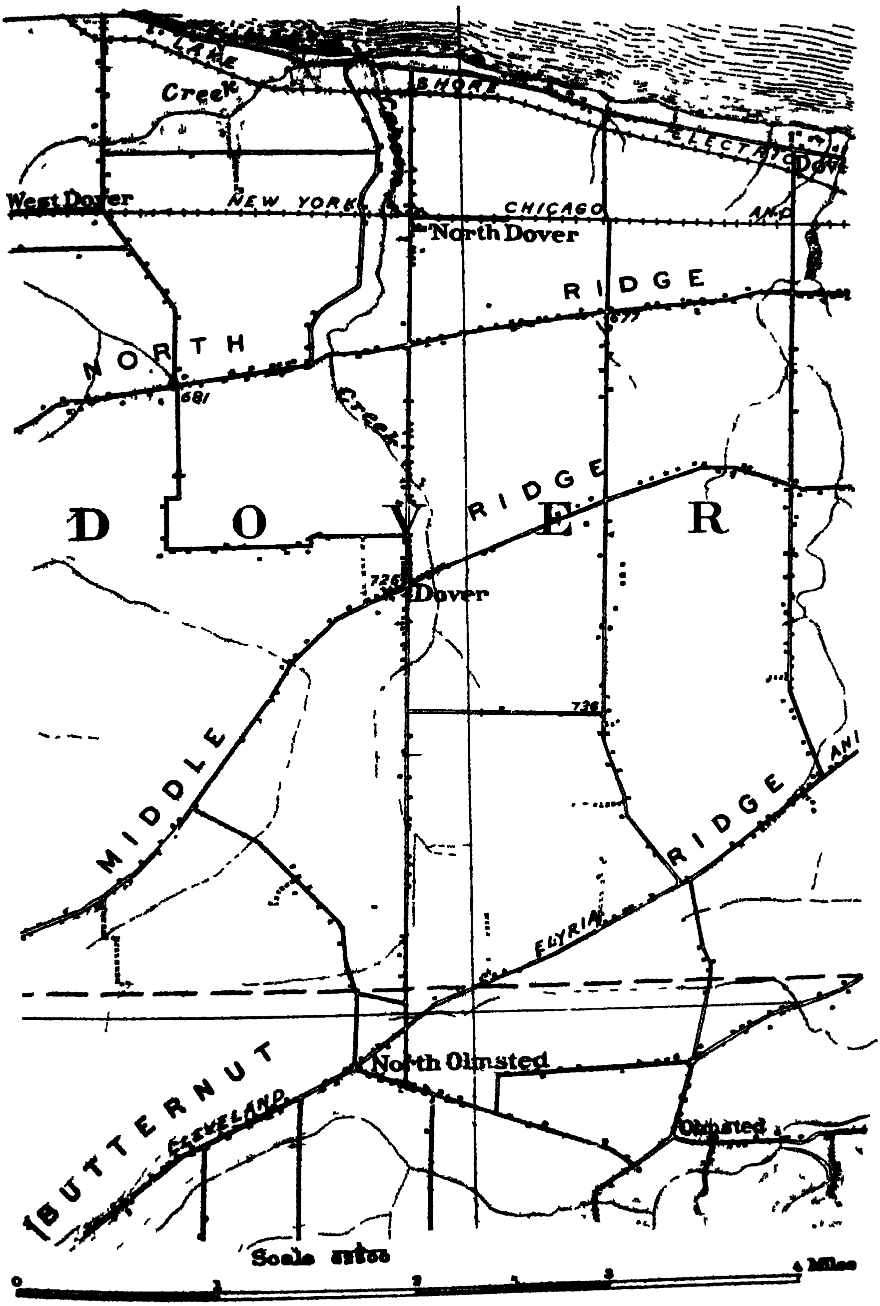



FIG. 22-10 B. Abandoned beach ridges. (U. S. Geological Survey)

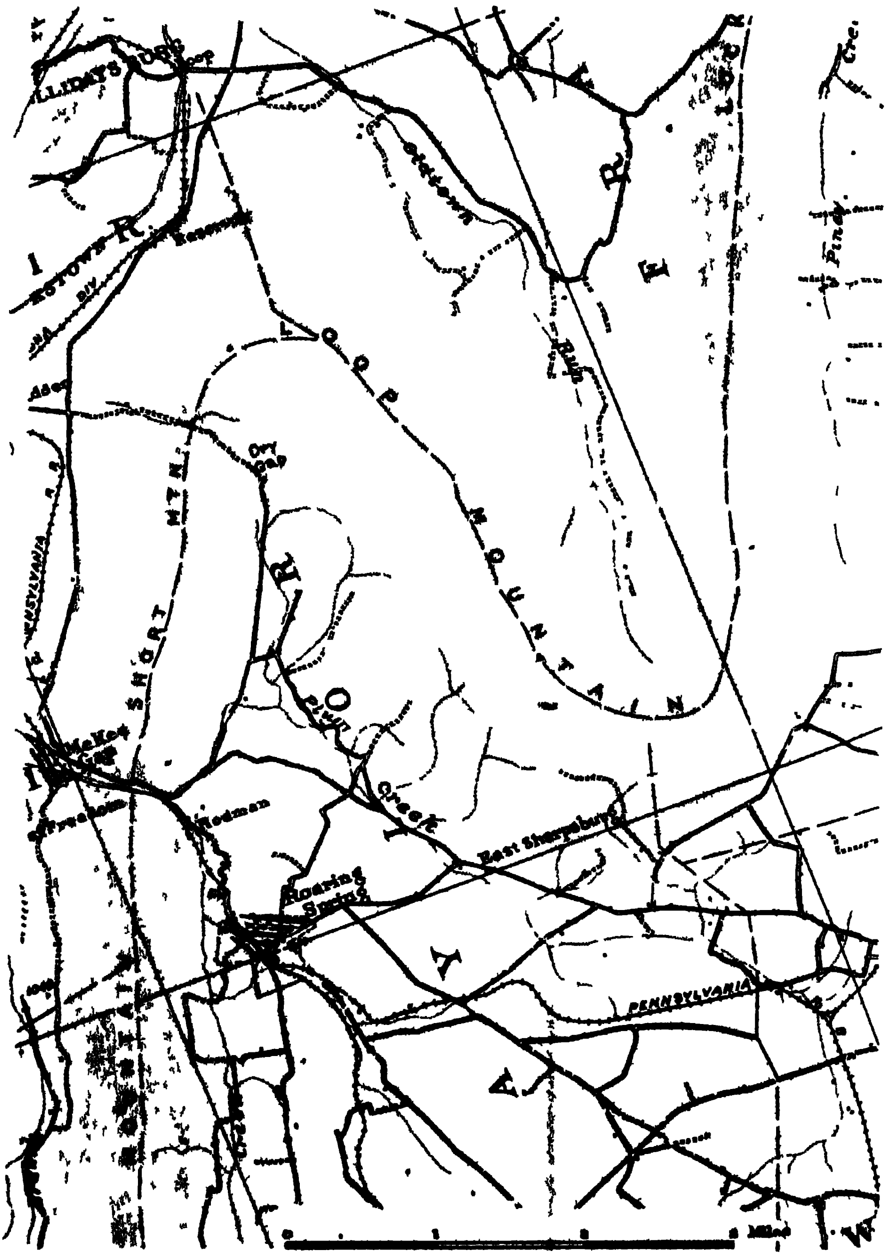



FIG. 22-14. Looped ridge. Note the difference in the slopes of the apices of the loops. The anticline is to the left, the syncline to the right. What is the direction of plunge? (U. S. Geological Survey)

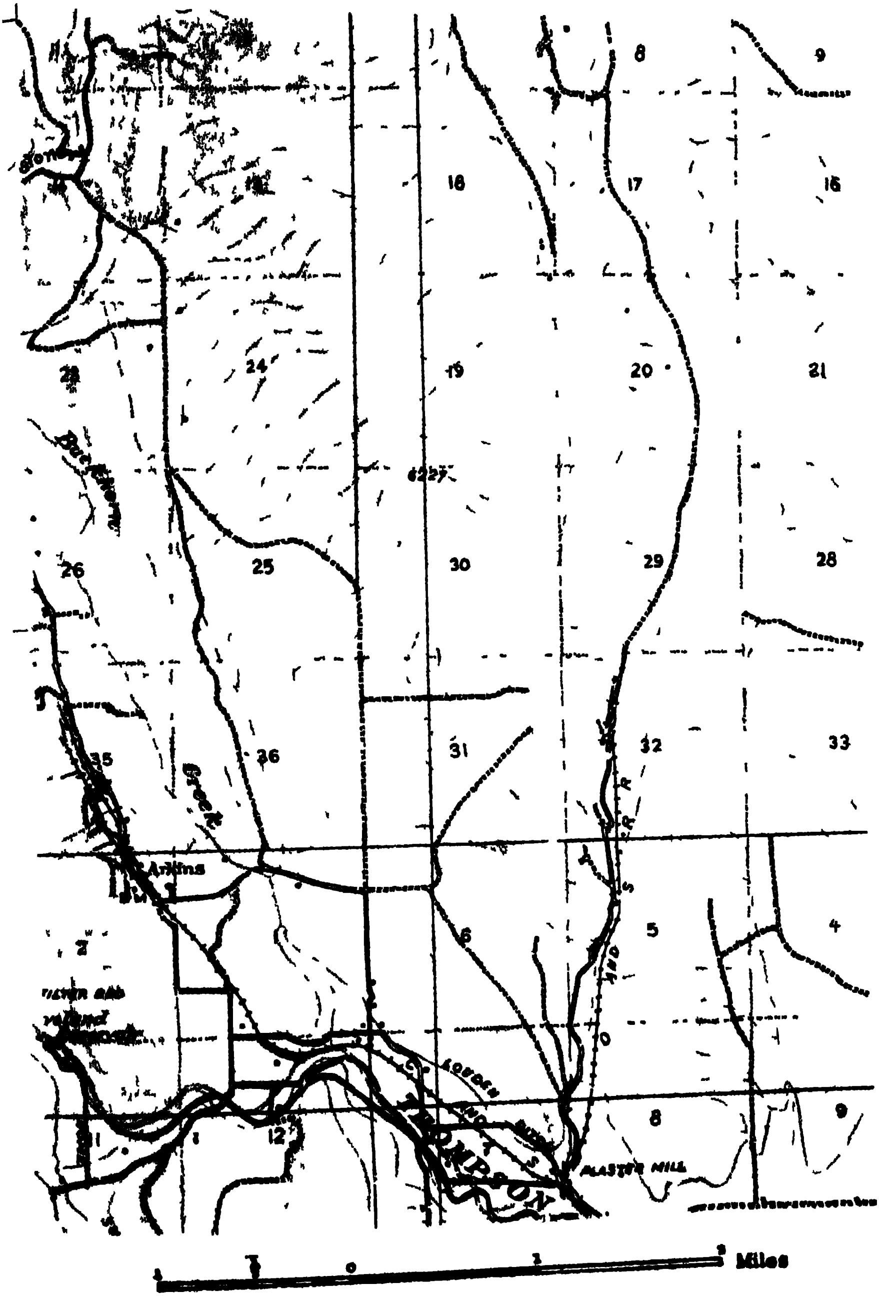



Fig. 22-15. Hogback ridges. (U. S. Geological Survey)

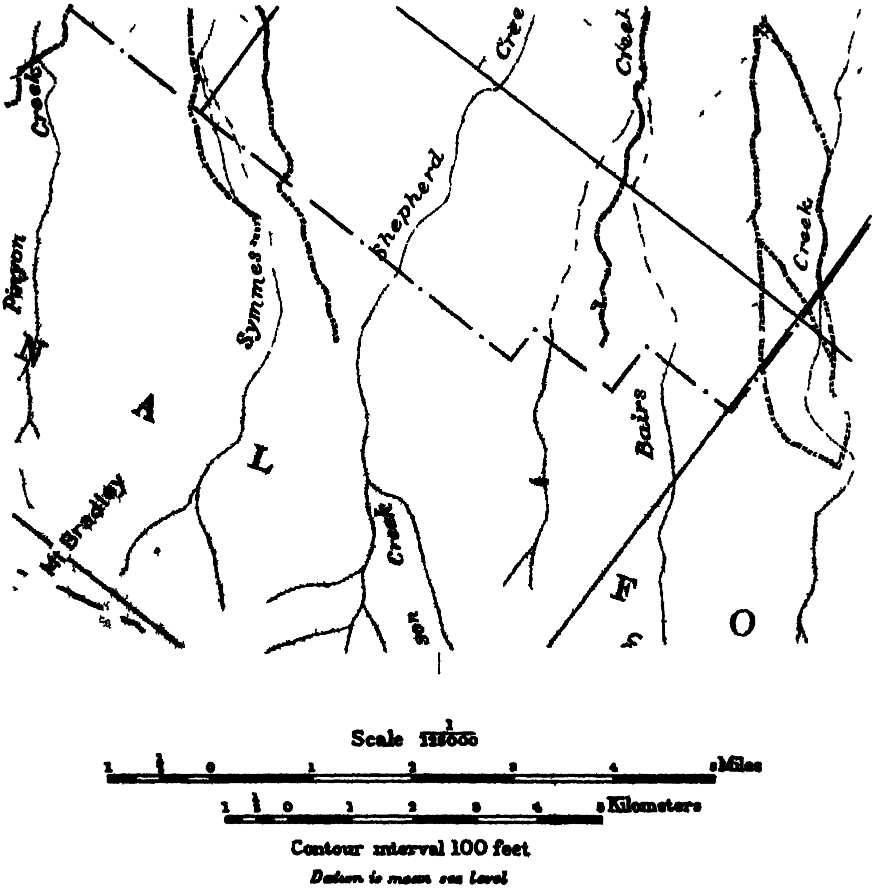



FIG. 22·16. Poorly expressed triangular fault facets. (U. S. Geological Survey)

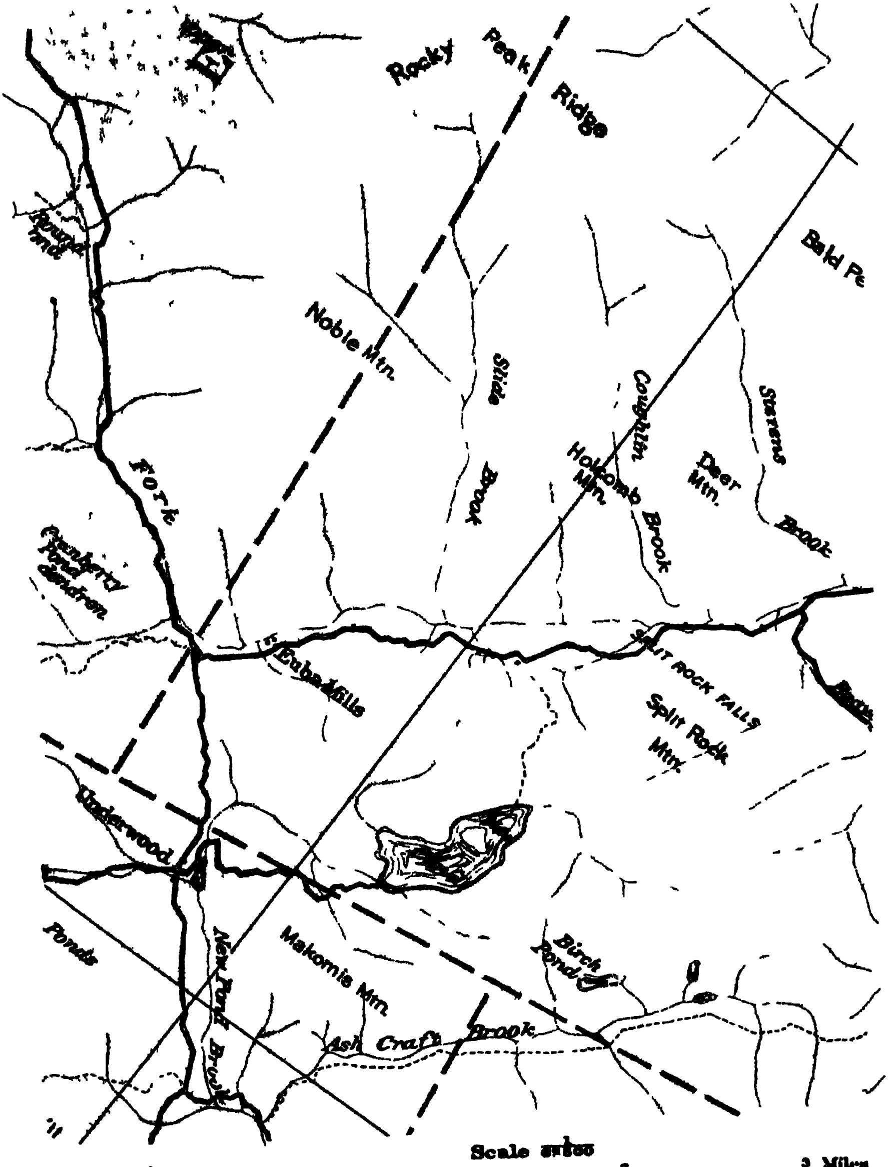



FIG. 22-18. Rectangular fracture pattern as indicated by drainage. Elizabethtown Quadrangle, New York. (U. S. Geological Survey)

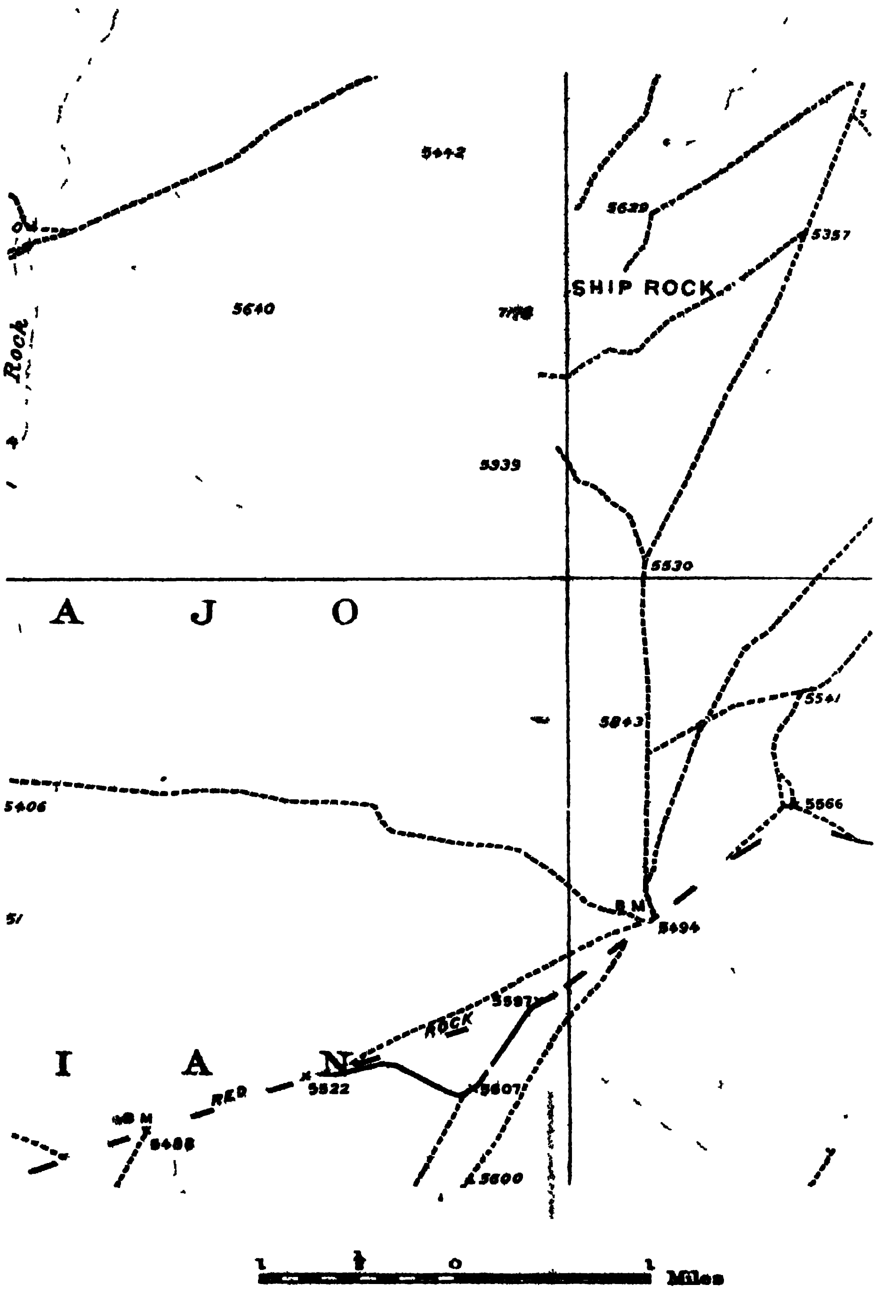



FIG. 22-19 B. Portion of Ship Rock, New Mexico, Quadrangle, showing volcanic neck and radiating dikes. Compare with aerial photograph of Fig. 22-19 A. (U. S. Geological Survey)

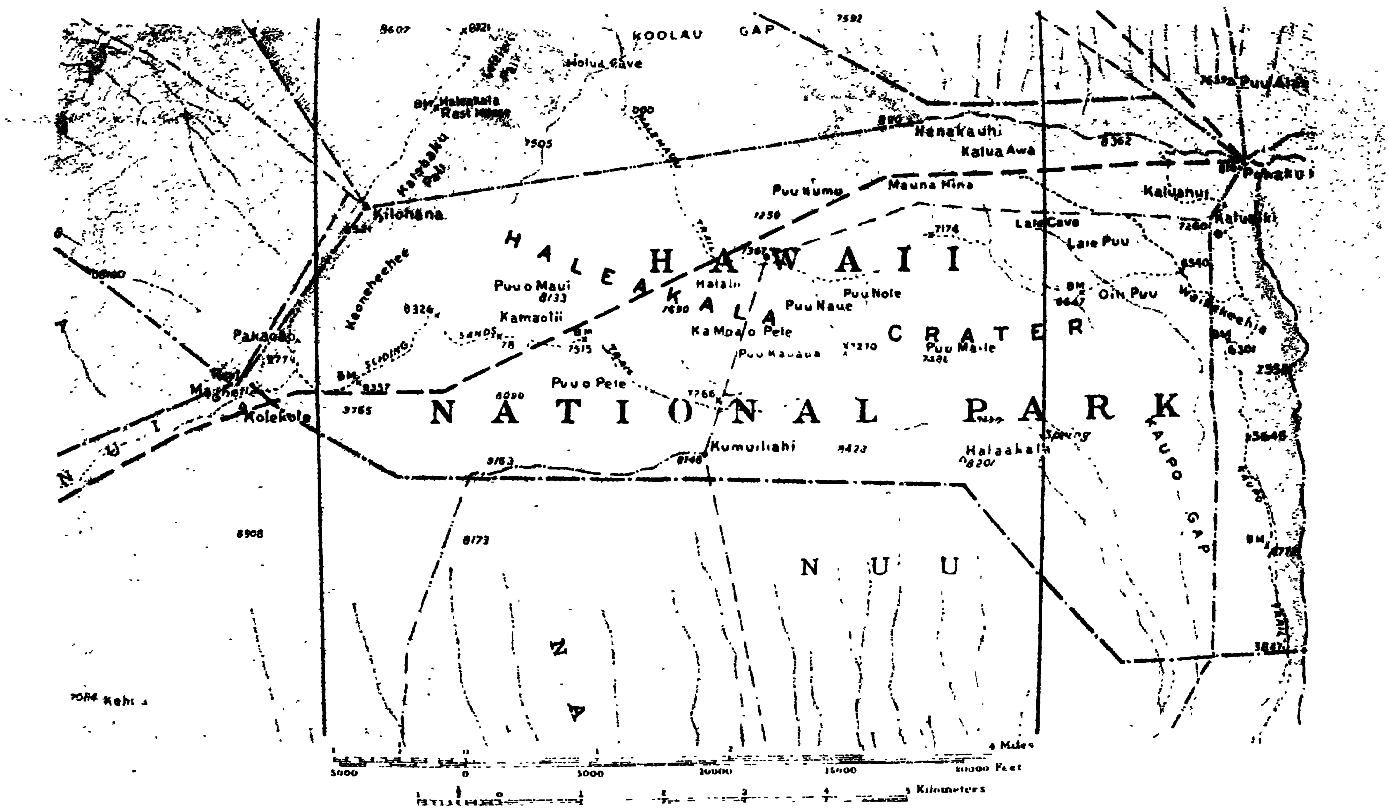



FIG. 22-22. Lava flows from Haleakala Crater, Territory of Hawaii. Note very rough surfaces of flows. Contour interval is 50 feet (U. S. Geological Survey)

merely by map inspection. Locally, intrusive masses have domed the country rock. Subsequent erosion may strip off the cover leaving a series of infacing scarps, cuestas, or hogbacks, concentrically surrounding the massive igneous core. Fig. 22-20 illustrates these relations.

***Igneous Extrusions.*** The principal topographic forms developed by volcanic extrusions are cones, craters, and lava flows. Where craters are preserved, and that is only in regions of active or recently active volcanism, little difficulty is encountered in identification of volcanic forms. Elsewhere, craters have been destroyed and topogra-

FIG. 22-20 Dome with igneous core and infacing sedimentary scarps encircling it (Courtesy of U. S. Department of Commerce, Civil Aeronautics Administration)

phy of volcanic origin must be recognized from other indications The conical shapes of volcanic mountains, even though much dissected or modified by erosion, persist long after craters have been destroyed. Many lava flows can be identified as radial bulges on the flanks of extinct volcanic mountains; as shown in Fig. 22-21

Spence Air Photos

FIG 22-21 Lava flow and cinder cones east of San Francisco Peaks, near Flagstaff, Arizona

Dikes radiating from a common center suggest a volcanic origin for the central mass. Many lava flows that have not been much eroded show extremely rough surfaces, pitted and ragged in detail. The roughness is easily detected on airplane views and on some topographic maps, as shown on Fig. 22-22.* Other flows have ropey flow ridges roughly concentric, and convex in the direction of flow.

Lavas usually photograph with dark shade tones, and on either maps or photographs give the impression of plastic materials that have flowed down slope.

### References

DAKE, C. L., and BROWN, J. S., *Interpretation of Topographic* and *Geologic Maps,* McGraw-Hill: New York, 1925.

EARDLEY, A. J., *Aerial Photographs: Their Use and Interpretation,* Harper and Brothers: New York, 1942.

ECKEL, E. B., "Interpreting Geologic Maps for Engineers," in *Symposium on Surface and Subsurface Reconnaissance* Am. Soc. Testing Materials, Spec. Tech. Pub. No. 122, 1951, pp. 5-15.

JENKINS, D. S., BELCHER, D. J., GREGG, L. E., and WOODS, K. B., "The Origin, Distribution, and Airphoto Identification of United States Soils," *Technical Development Report No. 52,* Civil Aeronautics Administration, U. S. Department of Commerce: Washington, D. C., 1946. Has special reference to airport and highway engineering.

LOBECK, A. K., *Military Maps and Air Photographs,* McGraw-Hill: New York, 1944.

SMITH, H. T. U., *Aerial Photographs and Their Interpretation,* Appleton-Century: New York, 1943.

*Symposium, Appraisal of Terrain Conditions for Highway Engineering Purposes,* Highway Research Board, 1948.

# APPENDIX I

# SOURCES OF GEOLOGIC INFORMATION

Standard professional geological journals found in most technical libraries are:

*American Journal of Science*
*American Mineralogist*
*Bulletin of the American Association of Petroleum Geologists*
*Bulletin of the Geological Society of America*
*Economic Geology*
*Journal of Geology*
*Journal of Paleontology*
*Journal of Sedimentary Petrology*

The U. S. Geological Survey publishes also, a series of bulletins, professional papers, and monographs; and the various state geological organizations issue publications. Of highest utility are the bibliographies of North American geology issued by the U. S. Geological Survey. *U. S. Geological Survey Bulletins 746* and *747* index by author and subject geological publications on North America from 1785 to 1918. *U. S. Geological Survey Bulletin 823* indexes the literature from 1919 to 1928, and *Bulletin 937* from 1929 to 1939. Yearly bibliographies index the literature on North America since 1939.

Information can be had by writing to the U. S. Geological Survey, Washington, D. C., or to the various state surveys, the geological departments of most of the state universities, and many of the private universities and colleges.

The state geological surveys are:

Alabama Geological Survey, University, Alabama
Arizona Bureau of Mines, Tucson, Arizona
State Geologist, Little Rock, Arkansas
California Division of Mines, Department of Natural Resources, San Francisco, California
Colorado Geological Survey Board, Denver, Colorado
Connecticut Geological and Natural History Survey, Storrs, Connecticut
Florida Geological Survey, Tallahassee, Florida
Department of Mines, Mining, and Geology, Atlanta, Georgia
Idaho Bureau of Mines and Geology, Moscow, Idaho
Illinois Geological Survey, Urbana, Illinois
Indiana Division of Geology, Department of Conservation, Indianapolis, Indiana
Iowa Geological Survey, Iowa City, Iowa
State Geological Survey of Kansas, Lawrence, Kansas
Kentucky State Department of Mines and Minerals, Lexington, Kentucky
Louisiana Geological Survey, Baton Rouge, Louisiana
Maine Geological Survey, Augusta, Maine
Maryland Department Geology, Mines, and Water Resources, Baltimore Maryland
Michigan Geological Survey Division, Department of Conservation, Lansing, Michigan
Minnesota Geological Survey, Minneapolis, Minnesota
Mississippi Geological Survey, University, Mississippi
Missouri Geological Survey, and Water Resources, Rolla, Missouri
Montana State Bureau of Mines and Geology, Butte, Montana
Nebraska Geological Survey, Lincoln, Nebraska
Nevada State Bureau of Mines, Reno, Nevada
New Hampshire State Geologist, Durham, New Hampshire
New Jersey Division of Geology and Topography, Department of Conservation and Development, Trenton, New Jersey
New Mexico Bureau of Mines and Mineral Resources, Soccorro, New Mexico
New York State Museum, State Education Department, Albany, New York
North Carolina Department of Conservation and Development, Raleigh, North Carolina
North Dakota Geological Survey, Grand Forks, North Dakota

Geological Survey of Ohio, Columbus, Ohio
Oklahoma Geological Survey, Norman, Oklahoma
Oregon State Department of Geology and Mining Industries, Portland, Oregon
Pennsylvania Topographic and Geological Survey, Harrisburg, Pennsylvania
Rhode Island Mineral Resources Commission, Rhode Island Industrial Commission, Providence, Rhode Island
South Carolina Geological Survey, Columbia, South Carolina
South Dakota Geological Survey, Vermillion, South Dakota
Tennessee Division of Geology, Nashville, Tennessee
Texas Bureau of Economic Geology, University of Texas, Austin, Texas
Vermont Geological Survey, Burlington, Vermont
Virginia Geological Survey, Charlottesville, Virginia
Washington Division of Geology, Department of Conservation and Development, Pullman, Washington
West Virginia Geological and Economic Survey, Morgantown, West Virginia
Wisconsin Geological and Natural History Survey, Madison, Wisconsin
Geological Survey of Wyoming, Laramie, Wyoming

Information of Canadian Geology can be had from:

The Geological Survey of Canada, Ottawa
Alberta Department of Lands and Mines, Edmonton
British Columbia Department of Mines, Victoria
Manitoba Department of Mines and Natural Resources, Winnepeg
New Brunswick Department of Lands and Mines, Frederickton
Newfoundland Department of Mines, St. John's.
Nova Scotia Department of Public Works and Mines, Halifax
Ontario Department of Mines, Toronto
Quebec Department of Mines, Quebec
Saskatchewan Department of Natural Resources, Regina

## APPENDIX II

# THE PHYSICAL PROPERTIES OF SOME COMMON ROCK TYPES[1]

TABLE A. WEIGHT PER CUBIC FOOT

| *Material* | *Weight (lb/cu ft)* |
|---|---|
| Granite | 162–172 |
| Marble | 165–179 |
| Limestone | 117–175 |
| Slate | 168–180 |
| Quartzite | 165–170 |
| Sandstone | 119–168 |

TABLE B. COMPRESSIVE STRENGTH

| *Material* | *Compressive Strength (lb/in²)* |
|---|---|
| Granite | 5000–60,000 |
| Marble | 8000–27,000 |
| Limestone | 2600–28,000 |
| Sandstone | 5000–20,000 |
| Quartzite | 16,000–45,000 |
| Brick | 1000–20,000 |

TABLE C. TENSILE STRENGTH

| *Material* | *Tensile Strength (lb/in²)* |
|---|---|
| Granite | 427 to 711 |
| Limestone | 427 to 853 |
| Marble | 427 to 1280 |
| Sandstone | 142 to 427 |

[1] Tables A, B, D, E, G, H, I, J from Kessler and Sligh, *U. S. Bureau of Standards Research Paper R P 1320,* 1940. Tables C, F from *The International Critical Tables,* 1927.

### TABLE D. SHEARING STRENGTH

| *Material* | *Shearing Strength* ($lb/in^2$) |
|---|---|
| Granite | 3700–4800 |
| Slate | 2000–3600 |
| Marble | 1300–6500 |
| Limestone | 800–3600 |
| Sandstone | 300–3000 |

### TABLE E. FLEXURAL STRENGTH

| *Material* | *Modulus of Rupture* ($lb/in^2$) |
|---|---|
| Granite | 1380– 5550 |
| Marble | 600– 4000 |
| Limestone | 500– 2000 |
| Slate | 6000–15,000 |
| Sandstone | 700– 2300 |

### TABLE F. ELASTICITY

| *Material* | *Modulus of Elasticity* ($lb/in^2$) |
|---|---|
| Granite | 1,545,000 to 8,700,000 |
| Marble | 7,250,000 to 10,150,000 |
| Slate | 8,700,000 to 13,050,000 |
| Limestone | 4,350,000 to 8,700,000 |
| Sandstone | 2,320,000 to 1,885,000 |

### TABLE G. TOUGHNESS

(For this test the specimen was mounted securely on heavy cast-iron base. A steel plunger with the lower end rounded rests on the specimen, and a 2-kg weight is dropped on the plunger by a motor driven sprocket chain. The height of the first drop is 1 cm, and each succeeding drop is increased by 1 cm.)

| *Material* | *Toughness* | |
|---|---|---|
| | *Range* | *Average* |
| Granite | 7 to 28 | 13 |
| Diorite | 6 to 38 | 23 |
| Basalt | 5 to 40 | 20 |
| Diabase | 6 to 50 | 19 |
| Quartzite | 5 to 30 | 15 |
| Sandstone | 2 to 35 | 10 |
| Limestone | 5 to 20 | 7 |
| Marble | 2 to 23 | 6 |
| Slate | 10 to 25 | — |

### TABLE H. ABRASIVE HARDNESS

| *Material* | *$H_a$ Values* |
|---|---|
| Granite | 37 to 98 |
| Marble | 8 to 42 |
| Limestone | 1 to 24 |
| Sandstone | 2 to 26 |
| Slate | 6 to 12 |

### TABLE I. ABSORPTION

| *Material* | *Absorption by Weight (%)* |
|---|---|
| Granite | 0.07 to 0.30 |
| Marble | 0.06 to 0.45 |
| Slate | 0.01 to 0.60 |
| Quartzite | 0.10 to 2.00 |
| Sandstone | 2.00 to 12.00 |
| Brick | 0.20 to 30.00 |

### TABLE J. POROSITY

| *Material* | *Porosity (%)* |
|---|---|
| Granite | 0.4 to 3.84 |
| Marble | 0.4 to 2.1 |
| Slate | 0.1 to 1.7 |
| Quartzite | 1.5 to 2.9 |
| Sandstone | 1.9 to 27.3 |
| Limestone | 1.1 to 31.0 |

## APPENDIX III

# TABLES FOR THE IDENTIFICATION OF SOME OF THE COMMON MINERALS

The following tables have been compiled to assist in the identification of minerals. With some acquaintance, many of the common minerals are identified at sight without difficulty. Others require a few checks, and others still may require extensive tests to establish their identity.

*Use of the Tables.* The major divisions of minerals in these tables are based on differences of streak; thus four major divisions are separated. By consulting the "Key to the Tables" a mineral can be placed in one of these streak classes. The streak classes are divided into color groups, which in turn are separated into divisions with or without cleavage. A further subdivision is based on hardness relative to ordinary window glass.

In the determination of a mineral by these tables, therefore, the streak is determined, and the color of the mineral noted. It is then examined for cleavage, and its hardness determined. These observations fix the position of the mineral in one of the groups of the "Key to the Tables" and refers to the proper table for specific identification. Further checking through the proper table will usually eliminate all but the correct species. Physical properties vary within limits. Cleavage, for example, is not always well developed or readily recognizable. A number of the minerals, therefore, are described in several tables. It is hoped that this duplication

of descriptions will facilitate the running down of the individual species.

As an example of the procedure in identifying a mineral, the steps followed for a specific mineral might be indicated: the mineral is dark colored, almost black in appearance, very glassy. The streak is found to be uncolored. By examination of the specimen, its surfaces are seen to be irregular and no two surfaces are parallel; no "looking-glass" surfaces are present. Hammered, it breaks irregularly. It is found to scratch the hammerhead or a glass plate. Reference to the "Key to the Tables" shows that it falls in the "B" group because the streak is colorless. On the basis of color it belongs in the subdivision under "B" of "Very Dark to Black" minerals. Further, it falls in that group that "shows no cleavage" and "scratches glass." According to this preliminary identification, Table XIII is indicated. By that table, all but black tourmaline and smoky quartz are eliminated. In the column under "Remarks" it is noted that tourmaline commonly shows fine lengthwise parallel lines or striations. The mineral in hand shows no striations nor do the other specimens of the same mineral. It is identified therefore as smoky quartz.

One other example may be given. The mineral to be identified is red. The streak is found to be "white or colorless"; therefore the mineral falls in the "B" group. The color of the mineral places it in the "Yellow, Red, or Brown" subdivision. It is only with difficulty that the knife blade is scratched; the hardness, therefore, is about six, that is, the mineral "scratches glass." Because of the smooth regular breaking surfaces, it is placed in the group that "shows cleavage." These properties direct to Table XV (page 599). This table indicates that the mineral is either orthoclase or plagioclase. Under "Remarks," it is stated that plagioclase sometimes has striations on the cleavage surface. Such striations are not always visible to the naked eye; hence it is concluded that the mineral is feldspar, and probably orthoclase.

## KEY TO THE TABLES

| | TABLE |
|---|---|
| **A. STREAK—Very Dark to Black** | |
| *Color of Mineral: Silvery to Grey* | |
| Scratches glass | I |
| Will not scratch glass | II |
| *Color of Mineral: Dark Grey, Blue-black* | |
| Scratches glass | III |
| Will not scratch glass | IV |
| *Color of Mineral: Yellow, Red, or Brown* | |
| Scratches glass | V |
| Will not scratch glass | VI |
| **B. STREAK—White, Silvery to Medium Grey, or Pale Colored** | |
| *Color of Mineral: White, Silvery, Pale Colored, or Colorless* | |
| Shows cleavage | |
| Scratches glass | VII |
| Will not scratch glass | VIII |
| Shows no cleavage | |
| Scratches glass | IX |
| Will not scratch glass | X |
| *Color of Mineral: Very Dark to Black* | |
| Shows cleavage | |
| Scratches glass | XI |
| Will not scratch glass | XII |
| Shows no cleavage | |
| Scratches glass | XIII |
| Will not scratch glass | XIV |
| *Color of Mineral: Yellow, Red, or Brown* | |
| Shows cleavage | |
| Scratches glass | XV |
| Will not scratch glass | XVI |
| Shows no cleavage | |
| Scratches glass | XVII |
| Will not scratch glass | XVIII |
| *Color of Mineral: Blue, Green, or Violet* | |
| Shows cleavage | |
| Scratches glass | XIX |
| Will not scratch glass | XX |

| | |
|---|---|
| Shows no cleavage | |
| Scratches glass | XXI |
| Will not scratch glass | XXII |

**C. STREAK—Yellow, Red, or Brown**

*Color of Mineral: Very Dark to Black*

| | |
|---|---|
| Shows cleavage | |
| Scratches glass | XXIII |
| Will not scratch glass | XXIV |
| Shows no cleavage | |
| Scratches glass | XXV |

*Color of Mineral: Yellow, Red, or Brown*

| | |
|---|---|
| Shows cleavage | |
| Scratches glass | XXVI |
| Will not scratch glass | XXVII |
| Shows no cleavage | |
| Scratches glass | XXVIII |
| Will not scratch glass | XXIX |

**D. STREAK—Blue or Green**

| | |
|---|---|
| Shows cleavage | |
| Scratches glass | XXX |
| Will not scratch glass | XXXI |
| Shows no cleavage | XXXII |

### Abbreviations Used in Tables

dissem. = disseminated
gran. = granular
ign. = igneous
indist. = indistinct
ls. = limestone
med. = medium
meta. = metamorphic
prism. = prismatic
tab. = tabular
vitr. = vitreous
xls. = crystals
x-wise = crosswise

TABLE I

STREAK Very Dark to Black
COLOR Silvery to Grey
Scratches glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 5.5–6 | Silver to med grey | Grey black | Indistinct | Metallic | Granular, massive orthorhombic xls | Arsenopyrite $FeAsS$ | Xls are diamond-shaped, commonly with striations parallel to short diagonal. In veins |
| 6–6.5 | Pale brass to silver | Greenish black | Indistinct | Metallic | Xls tabular cox comb hatchet shaped also concretionary and compact | Marcasite $FeS_2$ | Lighter color than pyrite. In veins Also often associated with coal beds |

TABLE II

STREAK Very Dark to Black
COLOR Silvery to Grey
Will not scratch glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 1 | Bluish, lead grey | Med grey to black | 1 good | Metallic | Foliated, masses grains | Molybdenite $MoS_2$ | Marks paper In granites, marbles gneiss and quartz veins |
| 1 | Silvery grey to black | Black to med grey | 1 good | Metallic | Foliated scaly granular earthy | Graphite C | Greasy flaky, does not have bluish cast of Molybdenite Marks paper In schists, rare in pegmatite |
| 2.5 | Lead grey | Lead grey | 3 at 90° | Metallic | Cleavable masses, cubic xls, granular | Galena $PbS$ | Marks paper with difficulty Found most commonly in veins, disseminated in sediments |

TABLE III

**STREAK: Very Dark to Black**
**COLOR: Dark Grey, Blue-black**
**Scratches glass**

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 5–6 | Black to brownish-black | Iron to brownish-black | None | Metallic to sub-metallic | Plates, granular, massive, common in black sands | Ilmenite $FeTiO_3$ | Sometimes slightly magnetic. Igneous rocks. |
| 5–6 | Black to grey | Black | None | Metallic to dull | Compact, reniform, botryoidal, No xls. | Psilomelane $MnO_2$ with $MnO$, $H_2O$, $BaO$, $K_2O$, etc. | Often with sooty coating of pyrolusite. Often with limonite. |
| 5.5–6.5 | Black | Black | None | Metallic | Gran., massive, octahedral xls. | Magnetite $FeO.Fe_2O_3$ | Strongly attracted by magnet. In igneous and metamorphic rocks. |

## TABLE IV

**STREAK: Very Dark to Black**
**COLOR: Dark Grey, Blue, Black**
**Will not scratch glass**

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 1 | Bluish, Lead grey | Dark grey to black | 1 perfect | Metallic | Scaly, granular, foliated masses | Molybdenite $MoS_2$ | Bluish tint distinguishes it from graphite. Marks paper. In granite, marbles, gneisses, quartz veins. |
| 1–2 | Silvery to black | Black to silvery | 1 good | Metallic | Foliated masses scaly, granular, earthy | Graphite C | Marks paper. In schists, rare in pegmatites. |
| 1–3 | Brownish-black to dull black | Black | None | Metallic to dull | Earthy, porous to compact, no xls. | Wad (Bog Manganese) $MnO_2.nH_2O$ | In residual soil, clay, or swamp deposits. |
| 2 | Lead grey to dark grey | Med. to dark grey | Perfect, lengthwise | Metallic | Long xls. bladed, columnar, massive, granular | Stibnite $Sb_2S_3$ | Striations lengthwise of xl. In veins. |
| 2–2.5 | Black to grey | Black | None, splint.. | Dull, metallic | Columnar, granular, radial, dendritic, fibrous | Pyrolusite $MnO_2$ | Soots fingers. |
| 2.5 | Lead grey | Lead grey | 3 good at 90° | Metallic | Cleavable masses, cubes, granular | Galena PbS | Marks paper with difficulty. In veins, disseminated in sediments. |
| 2.5–3 | Dark grey | Dark grey to black | Indistinct | Metallic | Granular, massive | Chalcocite $Cu_2S$ | Often coated with blue or green copper carbonate. In veins. |
| 3.5–4 | Med. grey to black | Reddish brown to black | 1 perfect, lengthwise | Metallic to sub metallic | Prismatic xls. | Manganite $Mn_2O_3.H_2O$ | Striated lengthwise. Often in veins |

## TABLE V

**STREAK: Very Dark to Black**
**COLOR: Yellow, Red, or Brown**
**Scratches glass**

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 6–6.5 | Brass Yellow | Dark green to black | None | Metallic | Xls. (cubic) granular, massive | Pyrite $FeS_2$ | Xls. often show striae. Tarnishes brown to iridescent, in all types of rocks. |
| 6–6.5 | Pale brass to silvery | Greenish black | None | Metallic | Tab. to cox-comb xls. hatchet shaped, also massive | Marcasite $FeS_2$ | Lighter color than pyrite. In veins; common in coal beds. |

## TABLE VI

**STREAK: Very Dark to Black.**
**COLOR: Yellow, Red, or Brown**
**Will not scratch glass**

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 3 | Bronzy takes purple tarnish | Grey-black | None | Metallic | Massive, granular | Bornite $Cu_5FeS_4$ | Recognized by characteristic purple strain. In veins and rarely in pegmatites |
| 3.5–4 | Brass to gold yellow | Greenish-black | Indistinct | Metallic | Massive, granular | Chalcopyrite $CuFeS_2$ | Color and softness. In veins. schists. and gneisses. |
| 3.5-4.5 | Brownish-bronze | Dark grey to black | None | Metallic | Massive, granular | Pyrrhotite Fe-S. | Brown tarnish. Softer than pyrite In veins |

TABLE VII

STREAK: White, Silvery, Medium Grey
COLOR: White, Pale, Colorless
Shows cleavage
Scratches glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 5–6 | White, colorless, greenish, greyish, brownish | White | 3 seldom seen distinctly | Greasy to vitr. | Massive, disseminated, granular | Nephelite $NaAlSiO_4$ with K, etc. | Not associated with quartz which it resembles. Often with sodalite, cancrinite, and feldspar. In syenites. |
| 5–6 | Yellow, grey, reddish | White | 3, often indistinct | Vitr. to greasy | Massive, granular | Cancrinite $3Na_2Al_2Si_2O_8 \cdot Na_2CO_3.nH_2O$ | With nepheline and sodalite commonly. A feldspathoid. In syenites. |
| 5–6 | White, grey | White | 2, 56°, 124° | Vitr. | Bladed, columnar, fibrous | Tremolite (Amphibole) $Ca_2Mg_5Si_8O_{22}(OH)_2$ | Marbles, schists. |
| 5.5–6 | Colorless, white to pale green | White, grey-green | 2 at 90° sometimes not distinct | Vitr.-dull | Stout xls., massive, granular | Diopside (Pyroxene) $CaMg(SiO_3)_2$ | Basic ig. rocks and meta. limy rocks |
| 6–6.5 | White, reddish, grey, green | White | 2 at 90° | Vitr. | Tabular xls., granular, massive | Orthoclase (Feldspar) $KAlSi_3O_8$ | Cleavage, color, hardness. In granites, pegmatites, etc. |
| 6–6.5 | White, grey, bluish, reddish | White | 2 87°, 93° | Vitr. | Tabular xls., granular, massive | Plagioclase (Feldspar) $NaAlSi_3O_8$ $CaAl_2Si_2O_8$ | Fine striations sometimes seen on cleavage. Should always be looked for. In many rock types, especially in basic igneous rocks. |
| 6–7 | Blue, white, grey, greenish | White | 2 lengthwise 74° 106° | Vitr. | Tabular or bladed xls. | Kyanite $Al_2SiO_5$ | Streaky color, lengthwise hardness 4-5. Cross-wise 6-7. Near contacts. |

*Table VII is continued on next page*

TABLE VII—(Continued)

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 6–7 | White, grey, greyish brown, pale green | White | 1 lengthwise | Vitr silky | Fibrous radiating | Sillimanite $Al_2SiO_5$ | Near contacts, in gneisses and schists |
| 6–7 | White, grey to yellowish | White | 2 good 87° & 93° with good parting at acute angle | Vitr | Massive flattened xls sometimes very large | Spodumene $LiAl(SiO_3)_2$ | Silky sheen Parting gives amphibole like cleavage aspect In pegmatites |
| 6.5–7 | White, pink grey brown to nearly black | White | 2 Not always distinct | Vitr dull | Columnar xls | Andalusite $Al_2SiO$ | Cross section of xl may show crude cross Bumpy development on surfaces of metamorphics, often weathered into relief |
| 6.5–7.5 | Red, brown yellowish | White | Partings resembling cleavages | Vitr | Massive generally dodecahedral xls common in sand | Garnet $R^{II}_3R_2^{III}(SiO_4)_3$ Ca Mn Fe Al Cr | Abundant in some metamorphic rocks and contact zones of igneous rocks |
| 8 | Colorless, yellowish pinkish, bluish greenish | White | 1 distinct crosswise | Vitr | Prismatic xls granular | Topaz $Al_2(F\,OH)_2SiO_4$ | Xls often striated lengthwise hardness, cleavage In contact zones and pegmatites |
| 9 | Brownish grey black | White | Partings resembling cleavages | Vitr | Xls granular massive | Corundum $Al_2O$ | Hardness and barrel like xls Not found with quartz |

TABLE VIII

**STREAK** White, Silvery to Medium Grey
**COLOR** White, Colorless to Pale Color
**Shows cleavage**
**Will not scratch glass**

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 1 | Bluish lead grey | Silvery to black | 1 good | Metallic | Foliated masses, grains | Molybdenite $MoS_2$ | Bluish tint. Marks paper. In granite, marbles, gneisses, and quartz veins |
| 1–2 | Silvery to dark grey | Silvery to dark grey | 1 good | Metallic | Foliated scaly granular earthy | Graphite C | Greasy, flaky. Marks paper. In schists. Rare in pegmatites |
| 1–2.5 | White green grey | White | 1 good | Pearly to greasy | Foliated, granular fibrous, massive waxy | Talc $H_2Mg_3(SiO_3)_4$ | Non elastic flakes. Greasy feel. In metamorphics |
| 1.5–2 | White yellowish reddish | White | 3. 1 very good | Vitr silky pearly | Foliated diamond shaped xls. Massive fibrous, earthy | Gypsum $CaSO_4 \cdot 2H_2O$ | Non elastic flakes. In sediments |
| 2–2.5 | White colorless, reddish to bluish grey | White | 3 at 90° | Vitr | Granular cubic xls | Halite NaCl | Breaks into cubes. Common salt taste. In sediments |
| 2–3 | White, colorless yellowish pale brownish | White | 1 perfect | Pearly to vitr | Foliated xls rare | Muscovite $K_2Al_4(Si_6Al_2)O_{20}(OH)_4$ | Flakes elastic. Very common in many rock types |
| 2–3 | Pink lilac yellowish | White | 1 perfect | Vitr to pearly | Grains xls scaly | Lepidolite $K_2Li_3Al_3(Si_6Al_2)O_{20}(F,OH)_4$ | In pegmatite often with colored tourmaline |

*Table VIII is continued on next page*

TABLE VIII—(Continued)

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 2.5–3.5 | White, light yellow to buff | White | 3 distinct | Vitr. to pearly | Tabular xls., platy | Barite $BaSO_4$ | High specific gravity and color. In veins. |
| 3 | White, yellowish, pinkish, bluish | White | 3 very good | Vitr. | Xls., grains, massive | Calcite $CaCO_3$ | Breaks into rhombohedrons. Fizzes in dilute HCl. Limestones, veins, marbles, secondary in igneous rocks. |
| 3.5–4 | White, yellowish, pinkish, bluish | White | 3 good | Vitr. | Xls., grains, massive | Dolomite $CaMg(CO_3)_2$ | Cleavages slightly curved. Reacts more slowly to dilute HCl than calcite. Marbles, dolomites, veins. |
| 3.5–4 | Yellow, brown, red, black | White, light to dark brown | 6 good | Resinous | Xls. massive, grains | Sphalerite ZnS | Often with other sulfides as galena, etc. in veins. |
| 3.5–4 | White, grey, yellowish, pinkish | White | 3 good | Vitr. | Chisel shaped, elongate needles | Aragonite $CaCO_3$ | Splintery, often in radiating needles. Sediments. |
| 3.5–4 | Yellowish, light to dark brown | White | 3 good | Vitr. to pearly | Xls., masses, granular | Siderite $FeCO_3$ | Magnetic after heating. |
| 4 | Purple, violet, white, colorless, green | White | 4 good | Vitr. | Octahedrons and cubes, granular | Fluorite $CaF_2$ | Xls. color, cleavage. Igneous rocks and veins. |
| 4–5 | Bluish, white, grey, greenish | White | 2 lengthwise | Vitr | Tabular or bladed xls | Kyanite $Al_2SiO$ | Note different hardness lengthwise and crosswise of xl Metamorphics |

TABLE IX

**STREAK:** White, Silvery or Medium Grey
**COLOR** White, Pale, to Colorless
No cleavage
Scratches glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 5–6 | Blue, grey, white | White | | Vitr. | Massive, grains | Sodalite $3NaAlSiO_4 \cdot NaCl$ | Not with quartz. Often with cancrinite and nepheline in syenite. |
| 5.5–6 | Varied, bluish, greenish, white, grey | White | | Vitr to pearly, greasy | Amorphous, botryoidal, stalactitic, etc. | Opal $SiO_2 \cdot nH_2O$ | Some varieties show play of colors, breaks with conchoidal fracture. |
| 6.5–7 | Pink to red and brown | White | | Vitr. | Dodecahedral xls., grains massive | Garnet $R^{II}_3R^{III}_2(SiO_4)_3$ Ca, Mn Fe Al Cr, Mg | Xl. form very common, esp in metamorphic rocks |
| 7 | White, pink, smoky, colorless, clear | White | | Vitr to greasy | Xls, grains, masses | Quartz $SiO_2$ | Very abundant. Rose variety in pegmatites; lavender quartz is called amethyst. |
| 7 | White, greyish, to black | White | | Dull to waxy or vitreous | Amorphous | Chalcedony $SiO_2$ | Agate, flint, etc. |
| 7–7.5 | Pink, green to blue black | White or pale colored | | Vitr | Triangular X-sections xls. elongate | Tourmaline Complex silicate of Na, Al, Fe, Mg, B, and OH | Commonly striated lengthwise of xls. Esp. in pegmatites and granites at contacts. |

*Table IX is continued on next page*

TABLE IX—(Continued)

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 7.5–8 | Pale green to white, bluish, pinkish, colorless | White | | Vitr. | Hexagonal xls., massive | Beryl $Be_3Al_2(SiO_3)_6$ | In pegmatites. Harder than quartz. Usually tinted. |
| 9 | Grey, brownish, bluish | White | | Vitr. | Hex. xls., masses | Corundum $Al_2O_3$ | Barrel shaped xls. hardness. |

TABLE X

**STREAK: White, Silvery to Medium Grey**
**COLOR: White, Silvery, Pale Colored**
**No cleavage**
**Will not scratch glass**

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 0–1 | White, grey, yellowish | Same color as mineral | | Earthy | Powdery | Chalk $CaCO_3$ | Fizzes in dilute acids. |
| 0–2 | white, buff, grey, reddish | Same color as mineral | | Earthy | Powdery grains coating on feldspars, masses | Kaolinite $H_4Al_2Si_2O_9$ | Adheres to tongue, chalk does not. In residual clays. |
| 1–2 | White, grey, yellowish, greenish, bluish | Light | | Silky | Fibrous, (parallel) felted | Chrysotile $H_4Mg_3Si_2O_9$ Asbestus and fibrous amphiboles | Chrysotile, fine flexible fiber; fibrous amphibole has coarser brittle fiber. |
| 1.5–2 | Grey, white, pinkish | White | | Vitr to pearly | Grains, aggregates | Gypsum $CaSO_4.2H_2O$ | In sediments. |

*Table X is continued on next page*

TABLE X–(Continued)

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 1.5–2.5 | Yellow, greenish, reddish, yellow, brownish, grey | White, pale yellow | | Dull to waxy | Granular, earthy, reniform | Sulfur S | In beds, esp, with gypsum, about volcanoes in decomposed sulfide rocks. |
| 1–3 | White, grey, yellow, red | Same color as mineral | | Earthy | Earthy, oolitic or pisolitic | Bauxite $Al_2O_3.nH_2O$ | Chemical weathering of syenites. |
| 2.5–3 | Silver | Silvery | | Metallic | Grains, scales | Silver Ag | Ductile, workable. In veins in igneous and metamorphic rocks. |
| 3 | Colorless, white, pinkish, bluish, yellowish | White | Indistinct | Vitr. | Granular xls. | Calcite $CaCO_3$ | May be aggregates where mineral cleavage is not discerned. Veins, limestones, marbles. |
| 3.5–4 | Colorless, white, pinkish, yellowish | White | Indistinct | Vitr. | Granular, masses, xls. | Dolomite $CaMg(CO_3)_2$ | Slower fizz than calcite and sometimes with curved cleavages. Veins, limestones, marbles. |
| 4.5–5 | Greenish, bluish, reddish | White | Poor | Vitr. | Granular, massive, hex. xls. | Apatite $Ca_5F(PO_4)_3$ | Sometimes distinctly cleavable. Pegmatites, granites, etc. |

TABLE XI

**STREAK: White, Silvery to Medium Grey**
**COLOR: Very Dark to Black**
**Shows cleavage**
**Scratches glass**

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 5–5.5 | Brown to black, reddish | White to pale | 2 fair | Vitr. | Tab. or wedge-shaped xls. | Titanite $CaSiTiO_5$ | Cleavage decidedly poorer than in hornblende. |
| 5–6 | White to dark grey | White | 2 lengthwise | Vitr. | Bladed, columnar, massive | Tremolite $Ca_2Mg_5Si_8O_{22}(OH)_2$ | An amphibole. In marbles. |
| 5–6 | Dark green to black | White to greenish or brownish | 2. good 56°-124° | Vitr. | Granular. elong. xls | Hornblende Complex silicate of Ca,Mg,Na,Al,Fe, OH | Common in igneous rocks (esp. diorites), schists and gneisses. |
| 5.5–6 | Dark green to black | White to pale green or brown | 2 90° fair. 1 better than other | Vitr. | Granular, chunky xls. | Augite $Ca(Mg,Fe)Si_2O_6$ with Mg,Al | In basic igneous rocks. |
| 6–6.5 | White to dark grey or bluish | White | 2 86°-94° | Vitr | Tabular xls., grains | Plagioclase $NaAlSi_3O_8$ $CaAl_2Si_2O_8$ | Striations sometimes visible on cleavage. In basic igneous rocks. |
| 6–7 | Green to brown to black | White, greenish, brownish | 1 lengthwise | Vitr. | Massive, elong. xls. | Epidote $Ca_2(AlFe)_3(SiO_4)_3(OH)$ | Commonly striated lengthwise |
| 6–7 | Blue, green, grey to nearly black | White | 2 lengthwise | Vitr. | Bladed xls. | Kyanite $Al_2SiO_5$ | Hardness lengthwise 4-5. Hardness crosswise 6-7. In metamorphic rocks. |
| 6.5–7.5 | Brown, grey to very dark | Light | 2, 89° 91° fair | Vitr to dull | Columnar xls. granular | Andalusite $Al_2SiO_5$ | Xls often nearly square in cross sections In schists |

*Table XI is continued on next page*

TABLE XI -(Continued)

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 6.5–7.5 | Dark brown, dark red to nearly black | Light | Partings resembling cleavage | Vitr. | Xls. massive grains | Garnet $R_2^{III}R_3^{II}(SiO_4)_3$ Ca,Mn,Fe,Al,Cr, Mg | Dodecahedral xls. common. In schists, gneisses and near contacts in igneous rocks. |
| 9 | Grey, brown to very dark | Light | Partings resembling cleavage | Vitr. | Barrel-shaped hex. xls. massive | Corundum $Al_2O_3$ | In syenites. |

TABLE XII

STREAK: White, Silvery, Medium Grey or Pale Colored
COLOR: Very Dark to Black
Shows cleavage
Will not scratch glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 1 | Bluish, lead grey | Med. grey to black | 1 good | Metallic | Foliated, masses, grains | Molybdenite $MoS_2$ | Marks paper. In granites, marbles, gneiss, and quartz veins. |
| 1–2 | Silvery to black | Black to med. grey | 1 good | Metallic | Foliated, scaly, granular, earthy | Graphite C | Greasy, flaky, does not have bluish cast of molybdenite. Marks paper. In schists. Rare in pegmatite. |
| 1–2.5 | Dark green, dark grey, to very dark | Light to med. | 1 perfect | Pearly | Foliated, masses | Talc $H_2Mg_3(SiO_3)_4$ | Greasy feel. In schists. |
| 1.5–2 | Red, brown, dark grey, to black | Light to med. | 3<br>1 very good | Vitr. to pearly | Xls. massive | Gypsum $CaSO_4.2H_2O$ | Flakes non-elastic. In sedimentary rocks. |

*Table XII is continued on next page*

TABLE XII—(Continued)

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 2–3 | Black to dark green or dark brown | Light to med. | 1 perfect | Vitr to pearly | Foliated masses, grains | Biotite $K_2(Mg,Fe)_6(Si,Al)_8O_{20}(OH)_4$ | Flakes elastic. Schists, gneisses, igneous rocks, pegmatites. |
| 3 | Reddish, brownish, bluish | White | 3 rhombohedral | Vitr. | Xls, grains, massive | Calcite $CaCO_3$ | Fizzes with acid. In marbles and limestones. |
| 3.5–4 | Reddish, brownish, dark | White | 3 rhombohedral | Vitr | Xls grains, massive | Dolomite $CaMg(CO_3)_2$ | Curved cleavages—slower reaction to acid than calcite. In marbles and limestones |
| 3.5–4 | Grey, yellow, brown to dark | White to light | 3 rhombohedral | Vitr., pearly | Xls. grains, massive | Siderite $FeCO_3$ | Brown color usually distinctive, different luster than sphalerite. In veins, limestones, marbles. |
| 3.5–4 | Yellow, brown, reddish, to black | Light | 6 fair to good | Resinous to vitr. | Xls grains, massive | Sphalerite ZnS | In veins. |
| 4–5 | Blue, grey to dark | White to pale | 2 lengthwise | Vitr. | Bladed xls | Kyanite $Al_2SiO_5$ | Hardness lengthwise 4-5. Hardness crosswise 6-7. In schists |

TABLE XIII

**STREAK:** White, Silvery, Medium Grey or Pale Colored.
**COLOR.** Very Dark to Black
Shows no cleavage
Scratches glass

| Hard-ness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 5–6 | Dark blue, dark grey | Light | | Vitr. | Massive, grains | Sodalite $3NaAlSiO_4.NaCl$ | With nepheline, cancrinite, etc. Not with quartz. In syenites. |
| 6–7 | Red, red-brown, black | Light | | Vitr. to metallic | Prismatic xls. massive, grains | Rutile $TiO_2$ | Often lengthwise striated, often minute needles in quartz. |
| 6–7 | Brown to black | Light | | Greasy to dull | Granular, massive | Cassiterite $SnO_2$ | Veins, pegmatites. |
| 6.5–7.5 | Brown, red to very dark | Light | Partings sometimes resembling cleavage | Vitr. | Dodecahedral xls., gran., massive | Garnet $R_3^{II}R_2^{III}(SiO_4)_3$ Ca,Mg,Fe,Mn,Al | Xls. common. In schists and gneisses and near contacts in igneous rocks. |
| 7 | Greyish to nearly black | White | | Vitr. | Xls. massive, grains | Smoky Quartz $SiO_2$ | Pegmatites. |
| 7 | Greyish to nearly black | Light | | Dull to waxy | Massive, botryoidal, banded | Chalcedony $SiO_2$ | When dark grey is called flint. |
| 7–7.5 | Black, blue, green | Light or pale colored | | Vitr. | Xls. grains, massive | Tourmaline Complex Silicate of Na,Al,Fe,Mg, B, and OH | Striated lengthwise commonly. In pegmatites and contact rocks. |
| 7–7.5 | Brown to dark grey to very dark | Light | Indistinct | Vitr., dull | Prismatic xls. | Staurolite $H_2FeAl_4Si_2O_{12}$ | Xls. often form a cross. In metamorphics—of clayey origin, slates, schists, and gneisses. |

*Table XIII is continued on next page*

TABLE XIII—(Continued)

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 9 | Brown, grey to very dark | Light | Parting ‖ to base | Vitr. | Hex. xls. | Corundum $Al_2O_3$ | Barrel shaped xls. Syenites, gneisses, schists. |



TABLE XIV

STREAK: White, Silvery, Medium or Pale Colored
COLOR: Very Dark to Black
Shows no cleavage
Will not scratch glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 3–4 | Green to very dark | Light | | Greasy, silky, dull | Massive, rarely fibrous | Serpentine $H_4Mg_3Si_2O_9$ | Altered basic igneous rocks. |

TABLE XV

**STREAK:** White, Silvery, Medium Grey or Pale Colored
**COLOR:** Yellow, Red, or Brown
Shows cleavage
Scratches glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 5–5.5 | Brownish, black, yellow, grey, green | White, pale | 2, 66-114 | Vitr. | Tabular or wedge-shaped xls. | Titanite $CaTiSiO_5$ | Generally in minute xls. |
| 5–6 | Green-black, brownish | Greyish, brownish, greenish, pale | 2, 60-120 | Vitr. | Elongate xls. gran., massive | Hornblende (Amphibole) Complex silicate of Na,Ca,Mg,Al, Fe,OH | In diorites, schists, etc. |
| 5–6 | Yellowish, brownish, grey, bluish | Light | 3 fair | Vitr. | Granular, massive | Cancrinite $3Na_2Al_2Si_2O_8.Na_2CO_3.nH_2O$ | In syenites with nepheline and sodalite, etc. |
| 5.5–6 | Green-black, brownish | Greenish, brownish, greyish, pale | 2 90° | Vitr. | Stumpy xls. granular, massive | Augite (Pyroxene) $Ca(Mg,Fe)Si_2O_6$ with Al,Mg | In basic igneous rocks. |
| 6 | Yellowish, green to brownish to dark green | White | 1 lengthwise | Vitr. | Slender xls. granular | Epidote $Ca_2(Al,Fe)_3Si_3O_{12}(OH)$ | Often striated lengthwise. Metamorphics. |
| 6–6.5 | White, greyish, reddish, yellowish, brownish | White | 2 90° | Vitr. | Tabular xls. granular, massive | Orthoclase Feldspar $KAlSi_3O_8$ | Single twinning. Granites, pegmatites, etc. |

*Table XV is continued on next page*

TABLE XV–(Continued)

| Hard-ness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 6–6.5 | White, grey, reddish, brownish | White | 2, 86°-94° | Vitr. | Tabular xls. granular, massive | Plagioclase Feld-spar $NaAlSi_3O_8$ and $CaAl_2Si_2O_8$ | Multiple twinning often seen as striations on cleavage. |
| 6.5–7 | Pinkish, brown to dark grey, almost black | Light | 2, 89°-90° | Vitr. to dull | Prismatic xls. granular | Andalusite $Al_2SiO_5$ | In schists, slates, gneisses. |
| 6.5–7.5 | Red, pink, brown | Pale to white | Partings may resemble cleavage | Vitr. | Dodecahedral xls. granular, massive | Garnet $R_3{}^{II}R_2{}^{III}(SiO_4)_3$ Al,Fe,Mg,Mn,Cr, Ca | Xls. common. In gneisses, schists and near contacts in igneous rocks. |
| 8 | Colorless, yellow, pinkish, bluish, greenish | White | 1 good crosswise | Vitr. | Prismatic xls. granular, massive | Topaz $Al_2(F,OH)_2SiO_4$ | Striated lengthwise. Pegmatites. |
| 9 | Brown, grey, black | Pale to white | X-parting may resemble cleavage | Vitr. | Hex prismatic xls., massive | Corundum $Al_2O_3$ | Barrel shaped xls. common. In gneisses, schists, syenites, marbles. |

TABLE XVI

**STREAK: White, Silvery, Medium Grey or Pale Colored**
**COLOR: Yellow, Red, or Brown**
**Shows cleavage**
**Will not scratch glass**

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 1.5–2 | White, reddish to yellowish, grey | White to pale | 3, 1 much better than others | Vitr. sometimes silky | Xls. granular, massive | Gypsum $CaSO_4.2H_2O$ | Flakes flexible but non-elastic, in limestone, clays, salt beds. |
| 2–2.5 | Yellowish, greyish, colorless | White | 3, 90° | Vitr. | Granular, cubic xls., massive | Halite NaCl | Taste, ordinary table salt. In ls. gypsum beds, etc. |
| 2.5–3.5 | White, yellowish | White to pale | 3 distinct | Vitr. | Tabular xls. massive | Barite $BaSO_4$ | Very heavy for size. In veins & residual lumps in soils, in some limestones. |
| 2–3 | White, yellowish, grey | White | 1 perfect | Pearly to vitr. | Foliated masses, hex. xls. | Muscovite $K_2Al_4(Si_6Al_2)O_{20}(OH)_4$ | Flakes elastic. In acid igneous rocks, gneisses, schists, and some sandstones. |
| 2–3 | Black, brown, yellowish-brown, greenish-black | Pale | 1 perfect | Pearly to vitr. | Foliated masses, xls. rare | Biotite $K_2(Mg,Fe)_6(SiAl)_8O_{20}(OH)_4$ | Flakes, elastic color dark. In acid and intermediate igneous rocks, gneisses and schists, some marbles. Mica |
| 2–3 | Pink to white | White | 1 perfect | Pearly to vitr. | Foliated masses, grains, xls. | Lepidolite $K_2Li_3Al_3(Si_6Al_2).O_{20}(F,OH)_4$ | Mica. Pink color. In pegmatites. |

*Table XVI is continued on next page*

TABLE XVI—(Continued)

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 3 | Colorless, white, yellowish, brownish, bluish, pink, reddish | White | 3 good rhombohedral | Vitr | Xls granular, masses | Calcite $CaCO_3$ | Fizzes in dilute acids. In limestones, marbles, veins, some igneous rocks. |
| 3.5–4 | Colorless, white, yellowish, brownish, pinkish, reddish | White | 3 good | Vitr. | Xls. granular, masses | Dolomite $CaMg(CO_3)_2$ | Reaction to acid less pronounced and slower than calcite. In dolomite beds. ls veins, marbles. |
| 3.5–4 | Yellow, brown to nearly black, greyish | White to pale yellow or brown | 3 good rhombohedral | Vitr. | Xls granular masses | Siderite $FeCO_3$ | In veins, ls. marbles. |
| 3.5–4 | Yellow, brown, black, reddish | White, shades of brown | 3 good rhombohedral | Resinous to vitr | Xls granular masses | Sphalerite $ZnS$ | In veins, limestones. Resinous luster characteristic |
| 4 | White, colorless, purple, pinkish, yellow, blue, green | White | 4 good | Vitr | Xls pyramidal cubic grains masses | Fluorite $CaF_2$ | In veins, occasionally in igneous rocks, as granite |
| 4.5–5 | Green, blue, violet, red, brown, | White | Sometimes shows cleavage | Vitr | Xls granular masses | Apatite $Ca_5F(PO_4)_3$ | In pegmatites marbles, and minute xls in most igneous rocks |

TABLE XVII

STREAK: White, Silvery, Medium Grey or Pale Colored
COLOR: Yellow, Red, or Brown
Shows no cleavage
Scratches glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 4.5–5 | Green, blue violet, red, brown | White | Sometimes shows 1 cleavage | Vitr | Xls massive, granular | Apatite $Ca_5F(PO_4)_3$ | in pegmatites, marbles, and minute xls. in most igneous rocks |
| 5–6 | Yellow, grey, reddish | White | 3, 60°, 120° | Vitr to greasy | Massive, granular | Cancrinite $3Na_2Al_2Si_2O_8$ $Na_2CO_3.nH_2O$ | With nepheline and sodalite commonly. A feldspathoid. In syenites. |
| 5.5–6.5 | White, yellow, red, brown, blue, colorless | White | | Vitr to pearly to dull | Amorphous | Opal $SiO_2.nH_2O$ | Some varieties show rich plan of colors. In cavities and veins |
| 6.5 | Brown, brownish green | White | Indistinct | Vitr. to resinous | Elongate prisms, granular | Idocrase (Vesuvianite) $Ca_6Al_4(F,OH)$ $Si_5O_{20}$ | In limestones close to igneous contacts. |
| 6–7 | Red reddish brown | White to light brown | | Vitr. | Prism xls. often bent, massive grains | Rutile $TiO_2$ | Tiny rods in quartz, in veins, and near igneous contacts. |
| 6–7 | Brown to black or dark grey | White to light brown | | Greasy, dull | Granular, stout xls. fibrous (wood tin) | Cassiterite $SnO_2$ | In granite, pegmatite, gneiss and as placers. |
| 6.5–7 | Green, yellowish, green, yellowish, brown | White, yellowish | Indistinct | Vitr. | Granular masses | Olivine $(Mg,Fe)_2SiO_4$ | In basic igneous rocks. Only common mineral. Green, glassy, granular. |

*Table XVII is continued on next page*

TABLE XVII—(Continued)

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 6.5–7.5 | Red brown to almost black | White to pale red or brown | Partings may resemble cleavages | Vitr | Dodecahedral xls common | Garnet $R^{II}_3R^{III}_2(SiO_4)_3$ Ca Mg,Fe Mn Al, Cr | In schists and gneisses and near contacts in igneous rocks Crystals common |
| 7 | Various shades reddish to black | White | | Vitr | Hex xls gran massive | Quartz $SiO_2$ | In acid igneous rocks, gneisses schists, sandstones veins vugs, etc Very common |
| 7 | White grey, yellowish brownish to black | White | | Dull waxy | Amorphous | Chalcedony $SiO_2$ | Concretions in sediments, cavities etc When very dark, called flint |
| 7–7.5 | Pink, green, blue, brown black | White light to blue green | | Vitr | Elongate prismatic xls massive | Tourmaline Complex silicate of Na Al Fe Mg B and OH | Striated lengthwise in pegmatite and near igneous contacts Triangular shape in X section common |
| 7–7.5 | Brown, yellowish, brown to brown black | White to grey to light brown | Sometimes shows 1 lengthwise | Vitr to dull | Prismat xls | Staurolite $H_2FeAl_4Si_2O_{12}$ | Xls often form crosses in metamorphics of argillaceous rocks slates schists gneisses |
| 7.5 | Yellow, reddish, brown | Light, white colorless | None | Vitr | Prismat xls Square cross section | Zircon $ZrSiO_4$ | Minute grains and crystals in igneous and metamorphic rocks |
| 9 | Brown, dark grey to light grey | White | Cross parting resembling cleavage | Vitr | Hex xls gran massive | Corundum $Al_2O_3$ | Barrel shaped xls massive In gneisses schists syenites marbles |

TABLE XVIII

STREAK: White, Silvery, Medium Grey or Pale Colored
COLOR: Yellow, Red, or Brown
Shows no cleavage
Will not scratch glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 0–2.5 | White, grey, yellowish, brownish | As color | | Earthy | Powdery, earthy | Kaolinite $H_4Al_2Si_2O_9$ | Chief constituent of residual clays. Sticks to tongue. |
| 1.5–2.5 | Yellow, brownish-yellow | White to pale yellow | | Waxy, dull, earthy | Granular, massive | Sulfur S | In beds with gypsum and with weathered sulfides (as pyrite) and about volcanic vents. |
| 3–4 | Green, yellowish-green, yellow | Light green to white | | Greasy, waxy, silky | Massive, some varieties fibrous | Serpentine $H_4Mg_3Si_2O_9$ | Alteration product in basic igneous rock; in some dolomite ls. |
| 4.5–5 | Green, blue, violet, red, brown | Light colored to white | Sometimes shows 1 cleavage | Vitr. | Xls. massive, granular | Apatite $Ca_5F(PO_4)_3$ | In pegmatites, marbles, and minute xls. in most igneous rocks. |

# TABLE XIX

**STREAK:** White, Silvery, Medium Grey or Pale Colored
**COLOR:** Blue, Green, or Violet
Shows cleavage
Scratches glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 4.5–5 | Green, greyish, brownish, yellowish, bluish, purple | White, grey, brownish-grey | Sometimes shows 1 | Vitr. | Prismatic xls. granular, massive | Apatite $Ca_5F(PO_4)_3$ | In pegmatites, marbles, and as minute xls. in most igneous rocks. |
| 5–6 | Blue, grey | Light | Sometimes | Vitr. | Massive, granular | Sodalite $3NaAlSiO_4 \cdot NaCl$ | With nepheline, cancrinite, etc. Not with quartz. In syenites. |
| 5–6 | Dark green, greyish or brownish ~~green to~~ black | Greenish, brownish-grey | 2 90° | Vitr. | Stumpy xls massive, granular | Augite (Pyroxene) $Ca(Mg,Fe)Si_2O_6$ (with Mg,Al) | In igneous rocks, especially the basic ores. Generally darker colored than diopside. |
| 5–6 | Pale green, colorless, white | Greenish-white | 2 90° | Vitr. | Stumpy xls. granular | Diopside (Pyroxene) $CaMgSi_2O_6$ | In contact rocks, especially those originally lims |
| 5–6 | Dark green, brownish-green to black | Greyish, brownish, greenish | 2, 56° & 124° | Vitr. | Elongate xls. massive, fibrous | Hornblende (Amphibole) Complex silicate of Ca,Mg,Fe,Al, Na,(OH) | In igneous rocks, especially diorite, schists, and gneisses |
| 5–6 | Pale to dark green | Greyish to greenish | 2, 56° & 124° | Vitr. | Elongate bladed xls granular, massive | Actinolite (Amphibole) $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$ | Generally lighter color than hornblende. In schists and contact rocks |

*Table XIX is continued on next page*

TABLE XIX—(Continued)

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 6–6.5 | White, grey, reddish-green | White | 2 90° | Vitr | Tabular xls. massive grains | Orthoclase (Microcline) $KAlSi_3O_8$ | Green variety comparatively rare. In igneous and metamorphic rocks, some sandstones. |
| 6–7 | Green, yellowish-green, brownish-green to black | Greyish | 1 lengthwise | Vitr. | Elongate xls. granular, massive | Epidote $Ca_2(Al,Fe)_3Si_3O_{12}(OH)$ | Often striated lengthwise. Contact zones and schists. Alteration of basic minerals by hot solutions. |
| (4–5) 6–7 | Blue, greyish, greenish to dark | Greyish | 2 lengthwise | Vitr. | Bladed xls. | Kyanite $Al_2SiO_5$ | Hardness lengthwise 4-5. Hardness crosswise 6-7. In schists. |

TABLE XX

STREAK: White, Silvery, Medium Grey or Pale Colored
COLOR: Blue, Green, or Violet
Shows cleavage
Will not scratch glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 1–2.5 | Light green, grey, white | White | 1 good | Pearly, greasy | Cleavable masses, waxy, massive | Talc $H_2Mg_3(SiO_3)_4$ | Greasy or slick feel. In schist. |
| 1–2.5 | Green to nearly black | Light green to grey | 1 good | Pearly, vitr. | Foliated masses, scales, granular masses | Chlorite Complex and variable silicate of Fe,Mg,Al, with $H_2O$ | Schists. Secondary in igneous rocks. Non-elastic flakes, color darker than talc. |

*Table XX is continued on next page*

TABLE XX—(Continued)

| Hard-ness | Color | Streak | Cleavage* | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 2–3 | Pink, lavender, yellowish | White | 1 perfect | Pearly to vitr. | Foliated grains, scaly, tabular xls. | Lepidolite $K_2Li_3Al_3(Si_6Al_2)O_{20}(F,OH)_4$ | In pegmatites, pink mica. |
| 2–3 | Greenish, yellowish, silvery, colorless | Light to white | 1 perfect | Pearly to vitr | Xls grains, masses | Muscovite $K_2Al_4(Si_6Al_2)O_{20}(OH)_4$ | Very common in acid igneous rock, schists, gneisses and some sediments (Mica). |
| 2–3 | Greenish-black, black, bronzy | Greenish to light | 1 perfect | Pearly to vitr | Xls grains, masses | Biotite $K_2(Mg,Fe)_6(Si,Al)_8O_{20}(OH)_4$ | Very common in igneous and metamorphics. Darker than muscovite. |
| 3 | Bluish, pinkish, yellowish, white, colorless | White | 3 rhombohedral | Vitr. | Xls. gran., massive | Calcite $CaCO_3$ | In limestones, marbles, veins. Fizzes in acid. |
| 3.5–4 | Brownish, yellowish, white | White | 3 rhombohedral | Vitr | Xls. gran., massive | Dolomite $CaMg(CO_3)_2$ | Cleavages frequently curved. In marbles, sedimentary beds, veins. |
| 4 | Violet, blue, green, colorless | White, pale | 4 good | Vitr | Cubic xls. granular | Fluorite $CaF_2$ | Common in veins and near contacts. |
| 4–5 | Bluish-grey, greenish | White, grey | 2 lengthwise | Vitr | Bladed xls | Kyanite $Al_2SiO_5$ | In schists and gneisses. Hardness lengthwise 4-5. Hardness crosswise 6-7. |
| 5 | Green, bluish, purple, brown, grey | Greenish, grey, white | Sometimes does not show cleavage | Vitr | Hex xls gran massive | Apatite $Ca_5F(PO_4)_3$ | In pegmatites, marbles, and as minute xls. in most igneous rocks |

TABLE XXI

**STREAK** White, Silvery, Medium Grey or Pale Colored
**COLOR** Blue, Green, or Violet
Shows no cleavage
Scratches glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 4.5–5 | Green, bluish green, purple, brown, grey | Light to grey | Sometimes shows poor cleavage | Vitr | Hex xls gran massive | Apatite $Ca_5F(PO_4)_3$ | In pegmatites, marbles, and as minute xls. in most igneous rocks. |
| 5–6 | Blue, reddish, greyish | White | Poor, often not seen | Vitr | Granular, massive | Sodalite $3NaAlSiO_4 \cdot NaCl$ | In syenites, with cancrinite and nepheline. Not with quartz Usually dark blue |
| 6–5 | Green, greenish, brown, brown, bluish | White | Indistinct | Vitr., resinous | Elongate prisms, granular | Idocrase (Vesuvianite) $Ca_6Al_3(F,OH)$ $Si_5O_{20}$ | In contact zones of limy rocks. |
| 6.5–7 | Green, yellowish green | White | Poor, generally not seen | Vitr | Granular | Olivine $(Mg,Fe)_2SiO_4$ | Only common mineral that is green, glassy, granular. In basic igneous rocks Some marbles. Not with quartz. |
| 7 | Violet, purple | White | | Vitr | Hex xls. | Amethyst (Quartz) $SiO_2$ | In veins and as cavity linings. |
| 7–7.5 | Green, blue, black | Greenish-bluish to pale | | Vitr. | Elongate xls. | Tourmaline Complex silicate of Na,Al,Mg,Fe, B, and OH | Generally shows lengthwise striations. In pegmatites and contact rocks. |
| 7.5–8 | Light to med green, grey white, bluish green | White | | Vitr | Hex xls. massive | Beryl $Be_3Al_2(SiO_3)_6$ | Pegmatites, sometimes in schists. |

# TABLE XXII

STREAK: White, Silvery, Medium Grey to Pale Colored
COLOR: Blue, Green, or Violet
Shows cleavage
Will not scratch glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 3–4 | Green, yellowish-green, yellow | White to pale green | | Waxy to silky to dull | Some varieties fibrous, massive | Serpentine $H_4Mg_3Si_2O_9$ | Fibrous, asbestos or chrysotile. Basic igneous rocks, marbles. |
| 4.5–5 | Green, bluish-green, violet, purple, brown | White to pale | Sometimes shows poor cleavage | Vitr. | Hex. xls. gran. massive | Apatite $Ca_5F(PO_4)_3$ | In pegmatites, marbles, and as minute xls. in most igneous rocks. |

# TABLE XXIII

STREAK: Yellow, Red, or Brown
COLOR. Very Dark to Black
Shows cleavage
Scratches glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 5–6 | Dark green, brownish-green to black | Brownish, greenish to grey | 2 good 56°-124° | Vitr. | Elongate xls. massive, gran. | Hornblende (Amphibole) Complex silicate of Ca,Mg,Fe,Al, Na,(OH) | In igneous rocks, esp. diorite, schists, and gneisses. |
| 5–6 | Dark green, brownish-green to black | Brownish, greenish to grey | 2 90° 1 better than other | Vitr. | Stumpy xls. massive, gran. | Augite (Pyroxene) $Ca(Mg,Fe)Si_2O_6$ with Mg,Al | In igneous rocks, especially the gabbros. |
| 5.5–6.5 | Black | Red-brown | Sometimes has well-developed parting resembling cleavage | Metallic, Bright | Granular, micaceous | Specular Hematite (Specularite) $Fe_2O_3$ | Igneous rocks, veins, sedimentary beds, and in some metamorphics. Red brown streak distinguishes it from limonite |

*Table XXIII is continued on next page*

TABLE XXIII—(Continued)

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 6–7 | Red, reddish-brown, black | Pale brown, white, grey | Sometimes seen | Metallic to vitr. | Prismat. xls. often bent | Rutile $TiO_2$ | In veins, contact rocks, often as hairs in quartz. |

TABLE XXIV

STREAK: Yellow, Red, or Brown
COLOR: Very Dark to Black
Shows cleavage
Will not scratch glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 2–3 | Black, dark brown, dark green, yellowish | Brownish to light | 1 perfect | Pearly to vitr. | Grains, masses, scales | Biotite $K_2(Mg,Fe)_6(Si,Al)_8O_{20}(OH)_4$ | In igneous and metamorphic rocks. Cleavage flakes tough and elastic. |
| 3.5–4 | Yellow, brown to almost black | Yellowish-brown | 3 (rhombohedral) | Vitr. pearly, dull | Granular, cleavable masses, rhombohedral xls. | Siderite $FeCO_3$ | In veins, limestones, marbles. |
| 3.5–4 | Brownish, yellowish to almost black | Yellowish-brown to grey | Dodecahedral | Resinous to vitr. | Granular, cleavable masses xls. | Sphalerite ZnS | In veins, disseminated in ls. Note luster on cleavage surface. |

TABLE XXV

STREAK Yellow Red or Brown
COLOR Very Dark to Black
Shows no cleavage
Scratches glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 5–5.5 | Brown yellow, yellow brown black | Yellowish yellow, brown | | Earthy silky | Earthy granular fibrous botryoidal | Limonite $2Fe_2O_3 3H_2O$ | Alteration product "rusting of some Fe mineral Very common |
| 5–6 | Black | Black sometimes brownish black | | Metallic to sub metallic | Platy granular | Ilmenite $FeTiO_3$ | Disseminated in igneous and metamorphic rocks |
| 5–6 | Black | Black brownish black | | Metallic dull | No xls massive botryoidal | Psilomelane $MnO_2$ with $H_2O$ MnO, etc | Usually with pyrolusite, often has sooty coating |
| 5.5 | Black | Dark brown | | Metallic to dull | Octahedral xls grain massive | Chromite $FeCr_2O_4$ | In basic igneous rocks Sometimes slightly magnetic |
| 5.5–6.5 | Grey, brown red to black | Red brown | Sometimes has well developed parting resembling cleavage | Sub metallic to dull or metallic | Granular micaceous (specularite) botryoidal massive | Hematite $Fe_2O_3$ | Igneous rocks, veins sedimentary beds and in some metamorphics Red brown streak distinguishes it from limonite |
| 6–7 | Black to reddish brown | White, grey to pale brown | | Metallic to vitr | Prismatic xls often bent | Rutile $TiO_2$ | Striated lengthwise In veins contact rocks, as hairlike inclusions in quartz |
| 6–7 | Brown to black yellowish brown | Grey brownish | | Greasy dull | Granular fibrous (wood tin) stout prismatic xls | Cassiterite $SnO_2$ | In granite pegmatite, gneiss placers |

## TABLE XXVI

STREAK: Yellow, Red, or Brown
COLOR: Yellow, Red, or Brown
Shows cleavage
Scratches glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 5–6 | Dark green, black or dark brown | Light, greenish, brownish | 2, 56° & 124° good | Vitr | Elongate xls gran., massive | Hornblende Complex silicate of Ca,Na,Mg,Fe, Al,(OH) | In igneous rocks, especially diorites, metamorphics. |
| 5–6 | Dark green, black or dark brown | Light, greenish, or brownish | 2 90° 1 better than other | Vitr. | Stumpy xls, gran., massive | Augite $Ca(Mg,Fe)Si_2O_6$ (with Al,Mg) | In igneous rocks especially gabbros. |

## TABLE XXVII

STREAK: Yellow, Red, or Brown
COLOR. Yellow, Red, or Brown
Shows cleavage
Will not scratch glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 3.5–4 | Yellow, brown to almost black | Yellowish, brownish | 3 rhombohedral | Vitr. | Xls. massive, granular | Siderite $FeCO_3$ | In veins, limestones, marbles. |
| 3.5–4 | Brownish, yellowish to almost black | Yellowish, brownish, grey | 6 good | Resinous | Xls. massive, granular | Sphalerite ZnS | In veins, disseminated in ls. Note luster on cleavage surface. |

TABLE XXVIII

STREAK: Yellow, Red, Brown
COLOR: Yellow, Red, Brown
Shows no cleavage
Scratches glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 5–5.5 | Yellow, brown, black | Yellow, brown | | Earthy, silky, dull | Earthy, gran., amorphous, fibrous, botryoidal | Limonite $2Fe_2O_3.3H_2O$ | Common alteration product of ferruginous materials. "Rust" very common. |
| 5.5 | Black | Brownish to black | | Metallic, sub-metallic | Octahedral xls. gran., massive | Chromite $FeCr_2O_4$ | In basic igneous rocks. |
| 5.5–6.5 | Grey, red, red-brown, black | Red, red-brown | | Sub-metallic, dull | Massive, gran., botryoidal, micaceous (black) (specularite) | Hematite $Fe_2O_3$ | Near igneous contacts; in sediments and metamorphics. |
| 6–7 | Red, red-brown, black | Grey, pale brown | Rarely shows 2 at 45° | Metallic | Prismatic xls. | Rutile $TiO_2$ | In veins, contact and metamorphic rocks, and as hairlike inclusions in quartz. |
| 6–7 | Brown to black | Greyish, brownish | | Greasy, dull | Gran., fibrous (wood tin) stout xls. sometimes knee-shaped | Cassiterite $SnO_2$ | In gneisses, granites, pegmatites, and placers. |

TABLE XXIX

STREAK Yellow Red or Brown
COLOR Yellow Red or Brown
Shows no cleavage
Will not scratch glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 0–2 | Yellow, brown | Yellow brownish | | Earthy | Earthy gran | Limonite (Yellow ochre) $3 Fe_2O_3 2H_2O$ | Alteration of ferruginous minerals iron rust Very common |
| 0–2 | Red | Red | | Earthy | Earthy gran | Hematite $Fe_2O_3$ Red Ochre | |
| 0–2.5 | Red scarlet | Scarlet to red brown | Indistinct | Dull to vitr | Earthy crusts granular | Cinnabar HgS | In veins disseminated in sandstone and ls Occurrence distinguishes it from red ochre |
| 1.5–2.5 | Yellow, greenish yellow, red yellow | White yellow | | Greasy, dull | Gran massive earthy | Sulfur S | In beds with salt and gypsum etc in altered parts of sulfides as pyrite |
| 2.5–3 | Copper red | Coppery | | Metallic | Scales branching masses | Copper Cu | Hackly cleavage in veins esp in basic lavas |
| 2.5–3 | Gold | Gold | | Metallic | Grains scales, lumps | Gold Au | In veins placers in sand and gravel Malleable, ductile |

TABLE XXX

**STREAK: Blue or Green**
**Shows cleavage**
**Scratches glass**

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 5–6 | Dark green, brownish to black | Light to greenish or brownish | 2 good 54° & 124° | Vitr. | Elongate xls., granular, massive | Hornblende Complex silicate of Na,Ca,Mg,Fe, Al,(OH) | Common in igneous rocks (esp. diorites) schists and gneisses. |
| 5–6 | Dark green, brownish-black | Light, greenish brownish | 2 90° 1 better than other | Vitr. | Stumpy xls. granular, massive | Augite $Ca(Mg,Fe)Si_2O_6$ Al, Mg) | Common in basic igneous rocks, esp. gabbros. |

## TABLE XXXI

STREAK Blue or Green
Shows cleavage
Will not scratch glass

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 1–2.5 | Green to nearly black | Light greenish grey | 1 perfect | Pearly to vitr | Scaly micaceous | Chlorite Complex and variable silicate of Fe Mg Al with $H_2O$ | Schists secondary in igneous rocks Non elastic flakes Color darker than talc |
| 3.5–4 | Green | Light green | 1 crosswise inconspicuous | Earthy silky vitr dull | Fibrous incrusting earthy | Malachite $Cu_2(OH)CO_3$ | With other copper minerals |
| 5–4 | Blue | Blue | 2 at 121° inconspicuous | Vitr to dull or earthy | Earthy fibrous incrusting | Azurite Cu (OH) (CO) | With other copper minerals |

## TABLE XXXII

STREAK Blue or Green
Shows no cleavage

| Hardness | Color | Streak | Cleavage | Luster | Structure | Name | Remarks |
|---|---|---|---|---|---|---|---|
| 7 7.5 | Blue black greenish | Bluish greenish (The finer the powder the lighter the streak) | None | Vitr | Columnar massive | Tourmaline Complex silicate Al Fe Na Mg B and OH) | Contacts of igneous rocks Pegmatites xls striated lengthwise triangular x section common |

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# SUBJECT INDEX

The symbol • indicates an illustration.
The symbol ★ indicates a three-color illustration in the section that follows page 568.